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HYDROMETEOROLOGICAL REPORT NO. 55A

(SUPERCEDES HYDROMETEOROLOGICAL REPORT NO. 55)

Probable Maximum Precipitation Estimates-United States Between the Continental Divide and the 103rd Meridian

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PREFACE TO REVISED EDITION

Hydrometeorological Report (HMR) No. 55 was published in 1984. This report was the first serious attempt to develop a PMP procedure for the highly orographic region between the Continental Divide and the 103rd meridian (CD-103 region). It superceded Technical Paper No. 38 (U.S. Weather Bureau 1960) west of the 105th meridian, where only broad-scale effects of terrain were considered, and HMR No. 51 (Schreiner and Riedel 1978) between the 103rd and 105th meridians.

The procedure used in HMR No. 55 is highly complex involving a number of subjective decisions based on meteorological experience and understanding. The procedure for orographic intensification in HMR No. 55 represented new thinking and was intended to provide a foundation for a technique that would be applicable to other complex orographic regions. Some of the concepts have since been adopted in NWS HYDRO 39 (Miller et al. 1984) and 41 (Fenn 1985), as well as HMR No. 56 (Zurndorfer et al. 1986).

Since the release of HMR No. 55 in early 1984, considerable controversy has developed regarding potentially high values in both general and local storm PMP estimates at higher elevations. It is these higher elevation storms where detailed observations and knowledge are lacking. In response to these concerns, the National Weather Service and the Bureau of Reclamation authors reexamined those parts of the study that might have influenced the results in these areas of concern. A number of decisions were made in HMR No. 55 that controlled the level of PMP estimates. Upon subsequent review, three areas were found where alternate decisions could be made. In combination, these alternate decisions significantly reduce the PMP estimates for small areas and short durations at higher elevations. These changes have been incorporated into this revised report, to be known as HMR No. 55A. Because some of the changes have resulted in significant differences to the 1984 results, <u>copies of HMR No. 55 should be discarded to avoid confusion.</u>

The following decisions were made:

1. To provide local-storm PMP estimates for the entire CD-103 region as opposed to the three sheltered geographic zones given in HMR No. 55. In HMR No. 55, we chose to restrict such estimates to the most sheltered zones. It appears reasonable that local-storm estimates can be provided throughout the region and allow the results to delineate the extent of control between local and general storm. This has been done and is discussed in chapter 12.

2. In HMR No. 55, the vertical moisture adjustment for local-storm PMP transposition somewhat departed from past practice. Use of one-half the liquid water variation observed in precipitable water tables (for a saturated pseudo-adiabatic atmosphere) considerably increased the estimates of PMP at higher elevation. The authors have changed this adjustment in HMR No. 55A to conform to previous studies that allow for the full moisture adjustment presented by the change in precipitable water with elevation.

3. HMR No. 55 treated the variation of 1- to 6-hr and 6- to 24-hr ratios in general storms with elevation such that the ratios were either constant or increasing with increasing elevation. In HMR No. 55A, the elevation variation of these ratios is treated differently, particularly on the most steep east-facing slopes of the Wind River and Big Horn range, and along the Rocky Mountains near Pikes Peak and portions of the Sangre de Cristo Mountains. For the most part the ratios drop off with increased elevation throughout the steep slope region.

The combined effect of these changes is discussed in section 10.3.3, where it is shown that general-storm reductions up to 40 percent are realized at some locations. Somewhat lower reductions (10-25 percent) are obtained from the local-storm procedure presented in section 12.4. Numerous other changes have been made to the text to make the discussion compatible with the changes mentioned above. Additional changes of a lesser nature have been included to correct typographical errors and other features noted in HMR No. 55 since its publication.

Because of user concern that this report be a stand-alone reference tool, the text has been prepared to read as an original study report, and only limited reference is made to differences from that presented in HMR No. 55. It is the authors' sincere intent that these modifications result in a minimum inconvenience in terms of their impact on design applications. The authors hope that this report has been strengthened by having taken the time to make the changes.

The reader is reminded that, as in the 1984 report, the results presented in this study represent a reasonable use of available storm data and state-of-the-art procedures. Knowledge of the many factors that influence the quantity of precipitation to fall at any specific location is still incomplete. Much research remains to be done in the area of orographic precipitation processes. As additional understanding develops, perhaps in the form of physical based models, or additional storm data, some changes to the present study may become necessary. While it is recognized there are some who consider these results to be overly conservative or highly controversial, the authors believe they have provided the best response to the definition of PMP available for this region at this time.

PROBABLE MAXIMUM PRECIPITATION ESTIMATES - UNITED STATES BETWEEN THE CONTINENTAL DIVIDE AND THE 103RD MERIDIAN

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ABSTRACT This study provides all-season general-storm probable maximum precipitation (PMP) estimates for durations from 1 to 72 hr for the region between the Continental Divide and the 103rd meridian. For the nonorographic portions of eastern Montana, Wyoming, North and South Dakota, Colorado, New Mexico and western Texas, estimates are available for area sizes from 10 to 20,000 mi^2. For orographic regions of these states east of the Continental Divide estimates are available for area sizes from 10 to 5,000 mi^2.

The study also provides estimates of local-storm PMP for the region. These estimates cover durations from 15 min to 6 hr and drainage areas between 1 and 500 mi^2.

A step-by-step procedure for computing PMP is presented for both the general- and local-storm criteria. An example has been worked out for the general-storm criteria.

1. INTRODUCTION

1.1 Background

Previously, generalized estimates of probable maximum precipitation (PMP) have been available for portions of the study region (United States between the Continental Divide and the 103rd meridian) in Technical Paper No. 38 (U.S. Weather Bureau 1960) and east of the 105th meridian in Hydrometeorological Report No. 51 (Schreiner and Riedel 1978) and 52 (Hansen et al. 1982). Technical Paper No. 38 (TP 38) applied to the region west of the 105th meridian but PMP values were restricted to areas less than 400 mi^2 and to durations up to 24 hr. Hydrometeorological Report No. 51 and 52 (HMR No. 51 and 52) provided PMP estimates for the region east of the 105th meridian, except the zone between the 103rd and 105th meridian was stippled to indicate an area where estimates may be deficient because terrain influences were not evaluated. Areas as large as 20,000 mi^2 and durations up to 72 hr were covered in these reports.

Additionally, estimates of PMP for individual drainages between the Continental Divide and the 103rd meridian have been prepared by the National Weather Service (NWS) on occasions where the prevailing generalized reports were believed to inadequately treat orographic influences. Throughout the United States, including the present study, the NWS has prepared generalized studies of PMP as requested by the Corps of Engineers (COE), the U.S. Bureau of Reclamation (USBR), the Soil Conservation Service (SCS), and the Tennessee Valley Authority (TVA).

The concept of generalized PMP studies should not connote a level of detail any less than that for the individual basin studies. The term generalized, in the sense of its use here, is to describe a study that covers a broad region involving numerous drainages. The primary advantages to generalized studies are to be found in the consistency of development and between results when determined for one drainage versus another. One disadvantage is the time required to complete such studies, in many instances taking up to three years.

The increasing development of the CD-103 region has caused renewed interest in the expansion of available water resources and in flood control. There is also concern for the hydrologic adequacy of many existing structures. The need existed, therefore, to review the estimates of precipitation potential for the region between the Continental Divide and the 103rd meridian and to expand the areas and durations covered in the previous study. The present study provides criteria for estimating PMP for durations from 1 to 72 hr for storm areas from 10 to 20,000 mi^2 in the eastern or nonorographic portion of this region and from 1 to 5,000 mi^2 in the more mountainous western portion.

In regions west of the Continental Divide, investigations have shown that PMP for small areas and short durations are not likely to occur in a general storm. The concept of a local storm has been used in western PMP studies to describe an intense, small-area, short-duration isolated event. East of the 105th meridian, previous studies have concluded that the general storm controls PMP for all durations. Since no known local storms have exceeded general storms in the east, it is assumed that the general storm includes sufficient convective bursts to envelop all local storms in that region.

In the present study, local-storm PMP has been defined for areas of 1 to 500 mi^2 and for durations of 15 min to 6 hr. Both local- and general-storm PMP are provided for the entire region between the Continental Divide and the 103rd meridian. It is incumbent upon the user to evaluate which storm type gives the controlling PMP for a specific area, duration, and location.

1.2 Authorization

Authorization for the study was the result of agreements among the U.S. Army Corps of Engineers, the U.S. Bureau of Reclamation, and the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS). Financing was provided by the COE through their continuing Memorandum of Understanding with the NWS and by the USBR under an Interagency Agreement with the NWS dated September 11, 1980.

1.3 Study Region

The northern and southern boundaries of the region are the borders of the United States with Canada and Mexico. HMR No. 51 provides generalized estimates of PMP for durations and areas east of the 105th meridian. In much of the region between the 103rd and 105th meridians, the PMP maps in HMR No. 51 were stippled to indicate some degree of uncertainty that could be resolved only when the region between the Continental Divide and the 105th meridian was studied. In the present report, PMP criteria for this two-degree-wide region have been included as a result of the present investigations, and the PMP estimates from this report supersede the criteria given in HMR No. 51. The eastern boundary of the study region is the 103rd meridian, while the western boundary is the Continental Divide.

West of the Divide, PMP estimates can be determined from Hydrometeorological Report No. 43, "Probable Maximum Precipitation Estimates, Northwest States" (U.S. Weather Bureau 1966), hereafter referred to as HMR No. 43, from Hydrometeorological Report No. 49, "Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages" (Hansen et al. 1977), hereafter referred to as HMR No. 49, or from Hydrometeorological Report No. 36, "Interim Report -- Probable Maximum Precipitation in California" (U.S. Weather Bureau 1961). Figure 1.1 shows the regions covered by the present report and the other reports mentioned. See Appendix A for a description of the geographic region and scope of each report.

The study region contains all or part of several major river basins. The entire Yellowstone and Powder River basins are within the study region. Only partially within this study region are the upper reaches of the Missouri, North and South Platte, Arkansas, Canadian, Pecos River basins, and the Rio Grande basin.

In summary, the study region extends from the Canadian to the Mexican borders between the Continental Divide and the 103rd meridian. For convenience, the study region will be referred to hereafter in this report as CD-103.

1.4 Method of Study

Procedures developed for PMP analysis must reflect the varied terrain effects throughout the CD-103 region. Terrain varies from the relatively flat regions of eastern Montana, Wyoming, Colorado, New Mexico, and western Texas to the mountainous region that approaches the Continental Divide. It was necessary to develop a procedure which would enable this diverse terrain to be analyzed in a consistent fashion. The adopted procedure is similar in basic development to that used in other studies in the western United States. The procedure separates total PMP into convergence and orographic components of precipitation. The convergence portion of the major storms in the region is determined to enable the estimation of convergence PMP throughout the region.

It is necessary to increase the estimates of convergence PMP for variations in orographic effects over the region to determine total PMP. In this report, an orographic factor, T/C, is derived from 100-yr 24-hr maps of NOAA Atlas 2 (Miller et al. 1973). Since the strength of atmospheric forces in the storm varies from the most intense 1-, 2-, 3-, or 6-hr period through the end of the storm, an intensity factor, M, was developed. This factor reduced the effect of orography

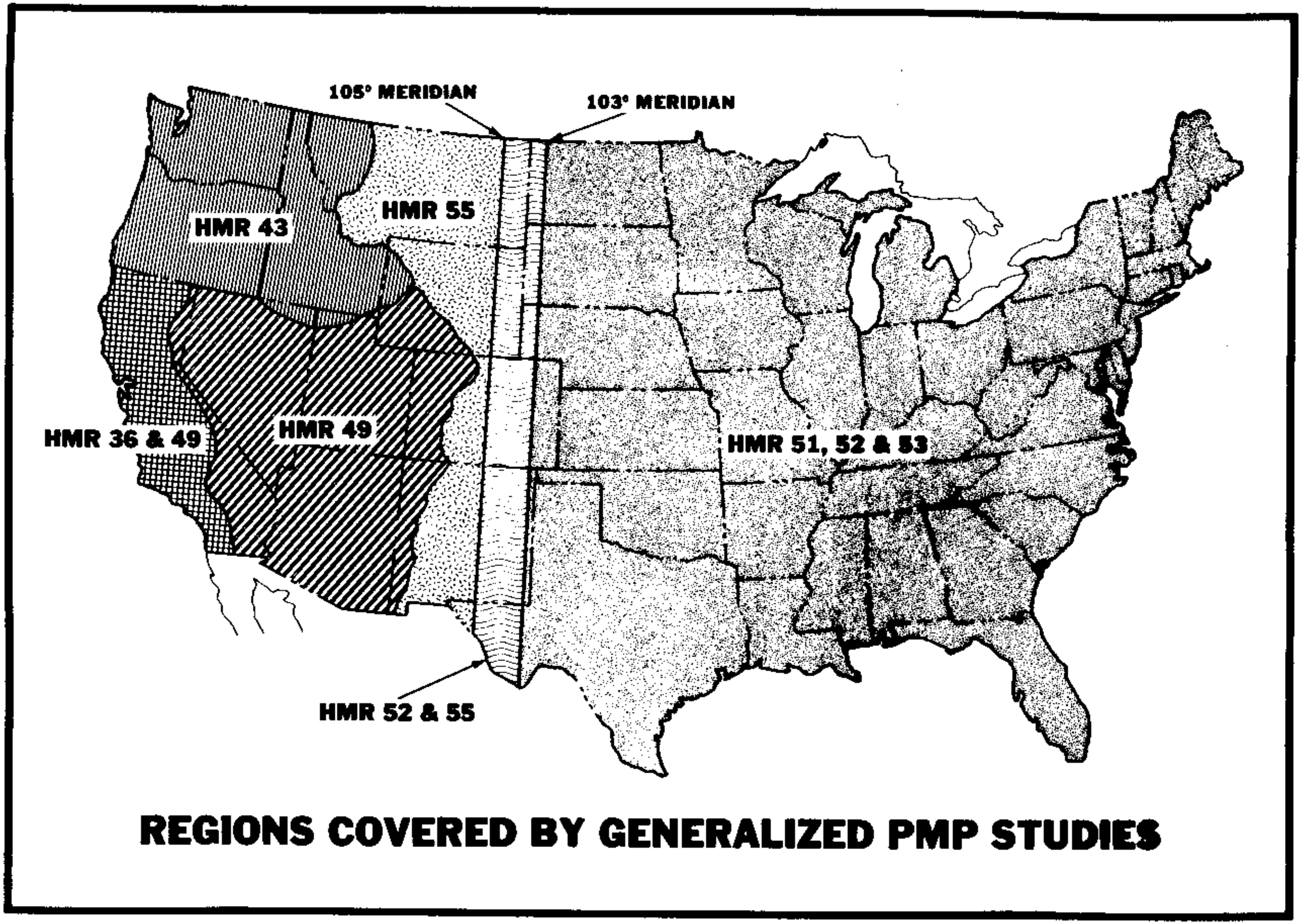


Figure 1.1.—Regions of the conterminous United States for which PMP estimates are provided in indicated Hydrometeorological Reports. See Appendix A for description of geographical region covered and scope of each report.

during the maximum 6-hr period of the maximum 24 hr of the storm. After determination of the 10-mi^2 24-hr PMP, 6-/24- and 72-/24-hr ratio maps were used to develop PMP values for the 10-mi^2 area for these other two key durations. A 1-hr 10-mi^2 general-storm PMP map was developed using a 1-/6-hr ratio map. The resulting 1-, 6-, 24-, and 72-hr 10-mi^2 PMP maps provide the key estimates of PMP for the region. Depth-area relations were developed to enable the user to provide estimates for other area sizes. The depth-area relations are based upon the depth-area characteristics of major storms in and near the region.

Local-storm criteria were developed from moisture maximization and transposition of major local-storm amounts throughout the study region. All observed major local storms were transposed to a common 5,000-ft elevation. Procedures are provided to adjust the PMP index values to other elevations. Depth-area and depth-duration relations keyed to the 1-mi^2 1-hr PMP map at 5,000 ft are provided.

1.5 Definitions

All Season. The largest or smallest value of a meteorological variable without regard to the time of the year it occurred. In this report, the largest PMP estimate determined without regard to the time of the year it may occur.

Among Storm. A storm characteristic determined when values of various parameters may be determined from different storms. For example, a 6-/24-hr ratio, where the 6-hr value is taken from a different storm than the 24-hr value.

Atmospheric Forces. The forces that result only from the pressure, temperature and moisture gradients and their relative changes with time over a particular location.

Basin Shape. The physical outline of the basin as determined from topographic charts or field survey.

Dew Point. The temperature to which a given parcel of air must be cooled at constant pressure and constant water-vapor content in order for saturation to occur.

Effective Elevation. The elevation at a point determined from a chart where topographic contours have been smoothed to reflect the effect of terrain on the precipitation process for a particular magnitude of storm. The actual elevation at the point may be either higher or lower than the effective elevation.

Effective Storm Duration. The time period within which 90 percent of the total storm precipitation occurs.

Generalized. When used as an adjective to modify names such as PMP or estimates or charts, is to be taken in the sense of "comprehensive," i.e., pertaining to all things belonging to a group or category. Thus, a generalized PMP map for a specific area and duration defines PMP for all points in the region; no location is excluded.

General Storm. A storm event which usually produces precipitation over areas in excess of 500 mi^2 and durations longer than 6 hr and is associated with a major synoptic weather feature.

Individualized. As applied to drainage estimates, indicates studies for specific drainages that include considerations for possible local influences. In the sense of applications to specific basins, it is commonly implied that information obtained from a generalized study will be processed and result in specific drainage-averaged values.

Local Storm. A storm event restricted in time and space. Precipitation rarely exceeds 6 hr in duration and the area covered by precipitation is less than 500 mi^2. Frequently local storms will last only 1 or 2 hr and precipitation will occur over only 100 or 200 mi^2. Precipitation in local storms is considered isolated from general-storm rainfall.

Module. A self-contained unit of a complex procedure.

Orographic Separation Line (OSL). A line separating regions where there are different orographic effects on precipitation. In one region, the nonorographic region, the only factors producing precipitation are atmospheric forces. In contrast, in the orographic region, precipitation results from a combination of atmospheric forces and lifting of air by terrain.

Probable Maximum Precipitation (PMP). Theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location at a certain time of the year.

Spatial Distribution. The geographic distribution of PMP for the storm area according to a storm with an idealized pattern.

Storm Centered. A characteristic of a storm that is always determined in relation to the maximum observed value in the storm as compared to the same factor for some other duration and area of the storm. For example, a storm-centered depth-area ratio relates the average depth over some specific isohyetal area of the storm that encloses the center of the storm to the amount at the storm center.

Temporal Distribution. The order in which incremental PMP amounts are arranged within the PMP storm. The time distribution within the local storm period is provided. The distribution of PMP values within the general storm is not discussed.

Total Storm Area and Total Storm Duration. The largest area size and longest duration for which depth-area-duration data are available for major storm rainfalls of record (sec. 2.2).

Within Storm. A storm characteristic determined when values of various parameters are required to be from the same storm. For example, a 6-/24-hr ratio where the values for each duration are always selected as the maximum values for the particular duration in the same storm (see also Among Storm).

Several additional terms that are used only in chapter 7 are defined at the beginning of that chapter.

1.6 Terrain Review

The region between the Continental Divide and the 103rd meridian is topographically one of the most complex regions in the conterminous United States. It is a region of steep slopes, narrow enclosed valleys, and open plains. To gain a greater understanding of this complex region, several of the study participants undertook an aerial reconnaissance of the entire region. Of particular importance was the topography at the locations of some of the more significant rainstorms that have occurred within the region: Gibson Dam, Warrick and Springbrook, MT; Savageton, WY; Big Thompson, Cherry Creek, Plum Creek, and Penrose, CO; and McColleum Ranch, NM. This aerial survey took place on three separate flights, and was conducted approximately 2,000-4,000 ft above the terrain. Figure 1.2 shows a schematic of the flight paths. A photographic record was made during these overflights. These photographs were referred to during early stages of the study to aid in understanding relative terrain influence.

1.7 Previous PMP Estimates for the CD-103 Region

The PMP values for this study are termed generalized or comprehensive estimates. By this it is meant isolines of PMP are given on index maps and depth-area relations are provided allowing determination of average storm-centered PMP for any drainage within the region. The present study has combined the latest storm data and current knowledge of the precipitation process to develop these estimates of PMP. Results from Weather Bureau Technical Paper No. 38 (U.S. Weather Bureau 1960), for the region between the Continental Divide and the 105th meridian, and HMR No. 51, for the region between the 105th and 103rd meridians, have been superseded by the present study.

Through the years, the Hydrometeorological Branch has provided PMP estimates for particular basins often referred to as individual drainage estimates. These estimates were provided if generalized PMP studies were not available, or if available generalized PMP estimates did not provide estimates for area sizes as large as the drainage under investigation. Of the more recent individual studies in the region considered in this report, only the one for the South Platte River, Hydrometeorological Report No. 44, "Probable Maximum Precipitation over South Platte River, Colorado, and Minnesota River, Minnesota (Riedel et al. 1969) has been published. In some situations, because of basin shape, unusual orographic considerations, areal or spatial distribution developed for the individual basin specific estimate, or other factors, the individual drainage estimate may take precedence. However, the applicability of the individual drainage estimate must be carefully evaluated on a case-by-case basis by a qualified hydrometeorologist, as the need arises.

1.8 Application of HMR No. 52 to PMP from this Study

Hydrometeorological Report No. 52, "Application of Probable Maximum Precipitation Estimates - United States East of the 105th Meridian" (HMR No. 52) (Hansen et al. 1982), was completed as an aid "...in adapting or applying PMP estimates from HMR No. 51 to a specific drainage." The procedures in HMR No. 52 are intended for application to nonorographic generalized PMP estimates and were done essentially independent of the base level PMP analyses. The present CD-103 study has introduced new delineations that limit the extent of nonorographic PMP within the 103°-105° region. This delineation is represented by the orographic

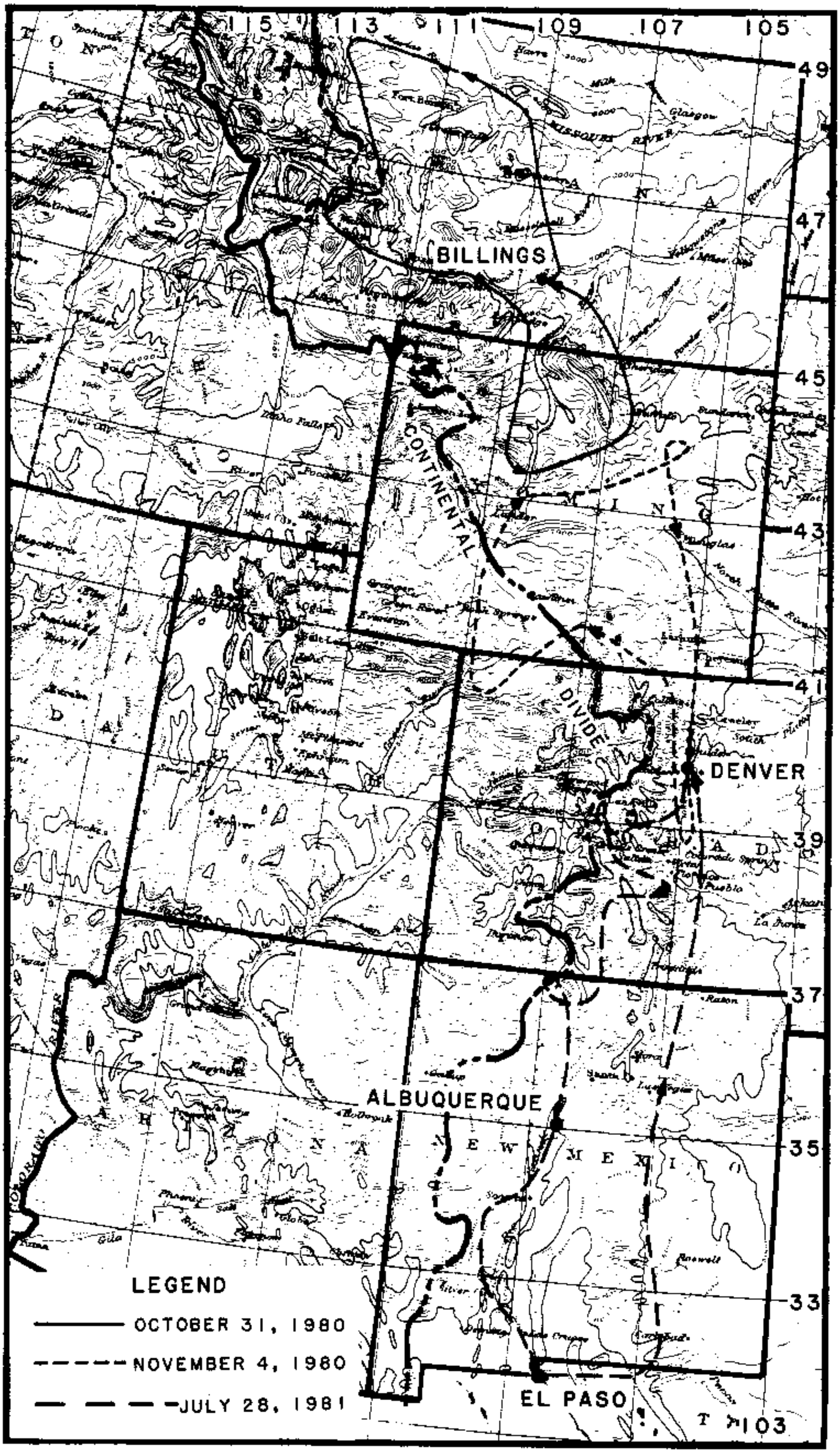


Figure 1.2.—General topography of CD-103 region with track of overflights shown.

separation line (sec. 3.2.1 and fig. 3.1). Since the western limit to the application of HMR No. 52, the 105th meridian, was set to be consistent with the geographical limits of HMR No. 51, consideration was given here to the reasonableness of changing the western limit to HMR No. 52.

The review led to the conclusion that a more appropriate western limit would be the orographic separation line. HMR No. 52 should be applied to PMP estimates from the present study between the 103rd meridian and the orographic separation line. However, for those nonorographic regions that lie west of the 105th meridian, yet east of the orographic separation line, notably in eastern Montana and Wyoming, the application of HMR No. 52 procedures should be considered tentative. Incomplete consideration was given to storms within this region to permit use of HMR No. 52 procedures without additional study. Such study will be a part of recommended future considerations discussed in chapter 15.

1.9 Organization of the Report

This report has been organized to provide a complete and logical progression through the various concepts, procedures, or methodologies used to develop the PMP estimates for the region. Sufficient background material is included in each chapter to give an understanding of the material without reference to other sources.

An important factor, basic to the development of any PMP estimate, is an understanding of the meteorology of major rain storms that have occurred in the region. Chapter 2 provides this information. Major storms that have occurred in and near the region are listed. A brief description is given of the weather situations and time and space distributions of the precipitation associated with some of the more important storms. The review of major storms leads to a storm classification system. This system differs from others that have been presented in previous hydrometeorological studies in that it is directed solely toward classifying storms on the basis of the primary causative factor for the precipitation over the region.

Chapter 3 presents a discussion of the topography of the region. The slope, elevation of the terrain, and intervening barriers to moist airflow are considered. The inflow directions of moist air in major storms discussed in chapter 2 were used to develop a terrain classification system and prepare an effective elevation and barrier map in chapter 3.

Moisture supply available for producing precipitation is among the more important factors in development of PMP estimates. The maximum available moisture within the region is discussed in chapter 4. Chapter 5 provides a discussion of the moisture that was available in the major storms that have occurred in and near the CD-103 region.

Chapter 6 provides an overview of the procedures used to develop the PMP estimates of this report.

Precipitation in the CD-103 region is produced by a combination of both orographic lifting and atmospheric forcing functions. In chapter 7, a procedure is explained that uses a comparison of individual precipitation observations, isohyetal analysis, evaluation of terrain, and evaluation of meteorological factors to estimate the relative contribution of atmospheric forces and terrain influences on precipitation in individual storms.

The traditional approach to developing PMP estimates is to maximize observed precipitation amounts for moisture and transpose these maximized values to other locations. The traditional approach to moisture maximization and transposition, as well as some modifications to these procedures, are discussed in chapter 8. Several different approaches were examined, each of which has advantages and disadvantages. These approaches were developed to extend the usefulness of the maximization and transposition procedure in orographic regions.

The basic procedure provides estimates of the amount of precipitation that results from free atmospheric forcing effects. These amounts were transposed throughout the CD-103 region. The amount of intensification that would occur at various locations as the result of terrain lifting was then estimated. The method of evaluating this orographic contribution and how it should be used to modify the convergence PMP is the subject of chapter 9.

An explanation of the development of the general-storm PMP index maps is given in chapter 10. Primary focus was given to 24-hr 10-mi^2 precipitation amounts, since station daily rainfall observations are most plentiful and modified transposition techniques can be developed with the greatest reliability for such small areas. Estimates were also developed for 1-, 6-, and 72-hr durations for the 10-mi^2 area.

To provide estimates for the range of area sizes and durations needed for this report, depth-area and depth-duration relations are required. Development of the depth-area relations is discussed in chapter 11. These procedures provide PMP estimates for 1, 6, 24, and 72 hr for area sizes to 20,000 mi^2 in nonorographic portions and 5,000 mi^2 in the orographic portions. These can be used to prepare depth-duration curves for any area size within the limits of the report.

The intermountain region between a generalized crestline of the Sierra Nevada and Cascade Mountains and the Continental Divide is relatively isolated from major moisture sources. Large precipitation amounts for very small areas and short durations in this region do not result from general storms. Within this region a local convective event, isolated in time and space, produces the maximum precipitation amount for these short durations and small areas. Chapter 12 discusses the development of the local-storm criteria.

The consistency and reliability of PMP estimates for various durations and area sizes are discussed in chapter 13. General comparisons are made with previous individual drainage estimates and generalized estimates within the region previously prepared by NWS. Comparisons are made with some major storm rainfall amounts. A final comparison is made with 100-yr return period values from NOAA Atlas 2 (Miller et al. 1973).

Chapter 14 focuses on the procedures for computing PMP for specific drainages. This chapter summarizes procedures developed and discussed in the earlier chapters of the report.

Chapter 15 provides some concluding remarks and suggestions for future studies. Particular attention is focused on studies which are needed to enhance the usefulness of the estimates developed in this and other PMP reports.

2. METEOROLOGY OF MAJOR STORMS IN THE CD-103 REGION

2.1 Introduction

The basic requirement for any study of the upper limits of precipitation within a region is the review of the major storms that have occurred in and near the study area. In a region so geographically extensive and so topographically diverse as the CD-103, the causes of major rainstorms have been many and varied. In the southern part of the region some of the major storms of record are a result of tropical storms that have crossed the Texas Gulf Coast and moved northwestward before recurving eastward. In Montana, the major storms are extratropical cyclones. Important throughout the region are extratropical storms that have embedded large convective cells, especially for small area sizes and short durations. In this study, we have made meteorological analyses of all of these various storm types to gain a more complete understanding of the meteorology of major rainstorms within the CD-103 region. This chapter describes a number of these storms to provide a basic knowledge of the causes of major storms in the CD-103 region.

2.2 Major Storms of Record

A survey was made of all the major storms that have occurred in and near the CD-103 region. The 82 major storms that occurred in this region are listed in chronological order in table 2.1. Location of the greatest rainfall amount from each of these storms is indicated in figure 2.1. The table provides an identifying storm number, name of location where the storm center occurred, date of occurrence, assignment number from the agency conducting the storm study (COE, USBR, and Atmospheric Environment Service of Canada), and the latitude and longitude of the center of rainfall. The storm identification numbers given in table 2.1 will be used throughout this report to identify the individual storms.

Table 2.1 also provides a chronological list of 35 additional major storms (supplemental storms, numbers 83-117) that occurred in the region just to the east of the CD-103 region (to 99°W). Locations of the rainfall centers of these storms are also plotted in figure 2.1. Some of these major storms are important to the estimation of PMP within the CD-103 region.

For most of these storms, depth-area-duration (DAD) data are available from Storm Rainfall in the United States (U.S. Corps of Engineers 1945-   ) or reviewed and approved by Bureau of Reclamation storm studies. An exception is the Gibson Dam storm, where a detailed reanalysis of isohyetal maps by the Bureau of Reclamation gave us the DAD data used in this study from a preliminary analysis. Complete storm studies are not available for those storms in which a dash appears under the heading Assignment Number in Table 2.1, where as a rule, the storms are for short durations (Virsylvia, Las Cruces, etc.).

It is apparent from examination of figure 2.1 that for large portions of the CD-103 region there are no major storms in the data base. The state of Wyoming is one such large region. Lack of sufficient storm data has always been a problem for most PMP studies and especially for arid and mountainous regions. One method employed in past hydrometeorological studies to resolve this deficiency is transposition of storms from other locations, i.e., assuming that the precipitation amounts that have occurred in another location could occur in

Table 2.1.--List of major storms of record considered in CD-103 study

Storm Number	Name	Storm Date	Assignment No.*	Latitude (°)	(')	Longitude (°)	(')
		Continental Divide-103° 00'					
1.	Ward District, CO	5/29-31/94	MR 6-14	40	04	105	32
2.	Adel, MT	6/29-7/1/98	MR 5-9	47	00	111	40
3.	Big Timber, MT	4/22-24/00	MR 5-10	45	50	109	57
4.	Canyon Ferry, MT	5/11-13/00	MR 5-11	46	38	111	42
5.	Kipp, MT	5/19-20/02	MR 5-12	48	30	112	45
6.	Boxelder, CO	5/1-3/04	MR 4-6	40	59	105	11
7.	Spearfish, SD	6/2-5/04	MR 4-8	44	29	103	47
8.	Rociada, NM	9/26-30/04	SW 1-6	35	52	105	20
9.	Elk, NM	7/21-25/05	GM 3-13	32	56	105	17
10.	Warrick, MT	6/6-8/06	MR 5-13	48	04	109	39
11.	Fort Meade, SD	6/12-13/07	MR 4-10	44	35	103	20
12.	Choteau, MT	6/21-23/07	MR 5-14	47	49	112	10
13.	Evans, MT	6/3-6/08	MR 5-15	47	11	111	08
14.	Norris, MT	5/22-24/09	-	45	35	111	41
15.	Half Moon Pass, MT	6/7-8/10	MR 5-17	46	39	109	18
16.	Knobles Ranch, MT	9/3-6/11	MR 5-18	48	55	111	33
17.	Bowen, MT	10/10-11/11	-	45	45	113	27
18.	Arnegard, ND	4/11-14/12	MR 5-19	47	50	103	25
19.	Fort Union, NM	6/6-12/13	SW 1-14	35	56	105	05
20.	Clayton, NM	4/29-5/2/14	SW 1-16	36	20	103	06
21.	Malta, MT	6/12-14/14	MR 5-20	48	21	107	53
22.	Adel, MT	6/1-5/15	MR 5-21	47	00	111	40
23.	Tajique, NM	7/19-28/15	SW 1-18	34	46	106	20
24.	Sun River Canyon, MT	6/19-22/16	R6-1-8	47	37	112	45
25.	Lakewood, NM	8/7-8/16	SW 1-20	32	38	104	21
26.	Pine Grove, MT	7/14-15/18	MR 5-23	46	50	109	05
27.	Meek, NM	9/15-17/19	GM 5-15B	33	41	105	11
28.	Browning, MT	9/27-28/19	MR 5-24	48	34	113	01
29.	Vale, SD	5/9-12/20	MR 4-17	44	37	103	24
30.	Fry's Ranch, CO	4/14-16/21	MR 4-19	40	43	105	43
31.	Penrose, CO	6/2-6/21	SW 1-23	38	27	105	04
32.	Springbrook, MT	6/17-21/21	MR 4-21	47	18	105	35
33.	Denver, CO	8/17-25/21	R4-1-8A	39	45	105	01
34.	Grover, CO	7/27-8/3/22	R4-1-9	39	45	105	32
35.	Virsylvia, NM (Cerro)	8/17/22	-	36	47	105	38

Table 2.1.—List of major storms of record considered in CD-103 study (continued)

Storm Number	Name	Storm Date	Assignment No.*	Latitude (°)	Latitude (')	Longitude (°)	Longitude (')
			Continental Divide-103° 00'				
36.	Hays, MT	6/16-21/23	MR 5-25	48	02	108	43
37.	Sheridan, WY	7/22-26/23	MR 4-22	44	55	106	55
38.	Savageton, WY	9/27-10/1/23	MR 4-23	43	52	105	47
39.	Sentinel Butte, ND	5/29-30/29	MR 4-27	46	57	103	49
40.	Beach, ND	6/6-7/29	MR 4-28	46	57	104	00
41.	Cheesman, CO	7/19-24/29	R4-1-15	39	13	105	17
42.	Valmora, NM	8/6-11/29	SW 2-27	35	49	104	56
43.	Gallinas Plt. St., NM	9/20-23/29	SW 2-28	35	09	105	39
44.	Porter, NM	10/9-12/30	SW 2-6	35	12	103	17
45.	Westcliffe, CO	4/19-22/33	R4-1-18	38	08	105	28
46.	Kassler, CO	9/9-11/33	R7-1-25A	39	30	105	06
47.	Cherry Creek, CO	5/30-31/35	MR 3-28A	39	13	104	32
48.	Las Cruces, NM	8/29-30/35	-	32	19	106	47
49.	Ragland, NM	5/26-30/37	GM 5-17	34	49	103	44
50.	Circle, MT	6/11-13/37	MR 5-29	47	30	105	34
51.	Leadville, CO	7/27/37	-	39	15	106	18
52.	Big Timber, MT	5/17-20/38	MR 5-6	45	50	109	57
53.	Loveland, CO	8/30-9/4/38	MR 5-8	40	23	105	04
54.	Waterdale, CO	8/31-9/4/38	R4-1-23	40	25	105	12
55.	Masonville, CO	9/10/38	-	40	26	105	13
56.	Prairieview, NM	5/20-25/41	GM 5-18	33	07	103	12
57.	Campbell Farm Camp, MT	9/6-8/41	MR 6-20	45	25	107	55
58.	McColleum Ranch, NM	9/20-23/41	GM 5-19	32	10	104	44
59.	Tularosa, NM	9/27-29/41	SW 3-1	33	04	106	02
60.	Rancho Grande, NM	8/29-9/1/42	SW 2-29	34	56	105	06
61.	Dooley, MT	3/13-17/43	MR 6-11	48	53	104	23
62.	Colony, WY	6/2-5/44	R6-1-23	44	56	104	12
63.	Dovetail, MT	6/14-18/44	R6-1-24	47	21	108	12
64.	Gering, NE	6/17-18/47	MR 7-16	41	49	103	41
65.	Plentywood, MT	8/10-13/47	R6-2-2	48	45	104	25
66.	Fort Collins, CO	5/30/48	MR 7-18	40	35	105	05
67.	Golden, CO	6/7/48	MR 7-19	39	44	105	14
68.	Dupuyer, MT	6/16-17/48	-	48	12	112	30
69.	Prospect Valley, CO	6/12-14/49	R7-2-5	40	05	104	26
70.	Marsland, NE	7/27-28/51	MR 10-7	42	36	103	06
71.	Belt, MT	6/1-4/53	-	47	25	110	50
72.	Buffalo Gap, Sask.	5/30/61	SASK-5-61	49	06	105	18
73.	Lafleche, Sask.	6/12-13/62	SASK-6-62	49	30	106	35
74.	Bracken, Sask.	7/13-14/62	SASK-7-62	49	10	108	10
75.	Gibson Dam, MT	6/6-8/64	-	48	32	113	33

Table 2.1.--List of major storms of record considered in CD-103 study (continued)

Storm Number	Name	Storm Date	Assignment No.*	Latitude (°)	Latitude (')	Longitude (°)	Longitude (')
			Continental Divide-103° 00'				
76.	Plum Creek, CO	6/13-20/65	-	39	05	104	20
77.	Big Elk Meadow, CO	5/4-8/69	-	40	16	105	25
78.	Rapid City, SD	6/9/72	-	44	12	103	31
79.	Broomfield, CO	5/5-6/73	-	39	55	105	06
80.	Wheatridge, CO	7/16/75	-	39	48	105	03
81.	Big Thompson, CO	7/31-8/1/76	-	40	25	105	26
82.	White Sands, NM	8/19/78	-	32	47	106	11
			Supplemental storms (103°00'-99°00')				
83.	Springfield, CO	4/4-5/00	-	37	24	102	37
84.	Wakeeney, KS	9/20-24/02	MR 1-8	39	01	99	53
85.	Knickerbocker, TX	8/4-6/06	GM 3-14	31	17	100	48
86.	May Valley, CO	10/18-19/08	SW 2-23	38	03	102	38
87.	Knickerbocker, TX	12/8-10/11	-	31	17	100	38
88.	Hazelton, ND	6/25-28/14	MR 4-14A	46	29	100	17
89.	Onida, SD	2/12-14/15	-	44	42	100	04
90.	Woodward, OK	9/29-10/2/23	MR 3-1B	36	30	99	25
91.	Eagle Pass, TX	5/27-29/25	GM 4-21	28	43	100	30
92.	Belvidere, SD	5/5-9/27	MR 4-25	43	50	101	16
93.	Berthold Agency, ND	7/5-8/28	UMV 1-18	48	20	101	46
94.	Wakeeney, KS	7/28-30/28	MR 3-18	39	01	99	53
95.	Hollis, OK	3/26-28/29	-	34	38	99	55
96.	Tribune, KS	6/2-6/32	SW 2-7A	38	28	101	46
97.	Mountain Home, TX	6/30-7/2/32	GM 5-1	30	10	99	21
98.	Abilene, TX	9/5-7/32	GM 5-16B	32	26	99	41
99.	Stratton, NE	9/11-12/33	R7-1-25B	40	08	101	13
100.	Cheyenne, OK	4/3-4/34	SW 2-11	35	37	99	40
101.	Hale, CO	5/30-31/35	°	39	36	102	08
102.	Segovia, TX	6/10-15/35	GM 5-2	30	22	99	38
103.	Tilston, Man.	6/29-7/1/35	MAN-6-35	49	23	101	19
104.	Ballinger, TX	9/2-7/35	GM 5-3	31	46	99	57
105.	Broome, TX	9/14-18/36	GM 5-7	31	47	100	50
106.	Sharon Springs, KS	5/30-31/38	MR 3-29	38	54	101	45
107.	Eldorado, TX	7/19-25/38	GM 5-10	30	46	100	44

Table 2.1.--List of major storms of record considered in CD-103 study (continued)

Storm Number	Name	Storm Date	Assignment No.*	Latitude (°)	(')	Longitude (°)	(')
		103°00' - 99°00'					
108.	Snyder, TX	6/19-20/39	-	32	44	100	55
109.	Kanton, OK	4/17-21/42	SW 3-6	36	55	102	58
110.	Brewster, NE	10/3-5/46	SW 3-2	41	57	99	52
111.	Del Rio, TX	6/23-24/48	-	29	22	100	37
112.	Vic Pierce, TX	6/23-28/54	SW 3-22	30	22	101	23
113.	Brandon, Man.	6/15-62	-	49	20	100	50
114.	Glen Ullin, ND	6/24/66	-	47	21	101	19
115.	Sombreretillo, Mex.	9/19-24/67	SW 3-24	26	18	99	55
116.	Medina, TX	8/1-4/78	-	29	55	99	21
117.	Albany, TX	8/1-4/78	-	32	45	99	20

* Assignment No's MR X-XX, GM X-XX, SW X-XX, and NP X-XX indicate formal storm studies completed by the U.S. Army Corps of Engineers, RX-X-XX indicates formal studies completed by Bureau of Reclamation, and SASK-X-XX indicates studies done by the Hydrometeorological Services Section, Atmospheric Environment Service, Canadian Department of the Environment. Where no number appears, the storm was studied by the Hydrometeorological Branch, National Weather Service as part of this or other hydrometeorological investigations.

° This center is part of the Cherry Creek, CO storm (47) and was contained in MR 3-28A. For the purposes of this study a separate analysis was made (see Appendix).

the region for which there is limited data. Justification for such transposition is based on the existence of meteorological homogeneity of storm conditions between the actual and transposed locations. Homogeneity implies that the storm mechanisms that operate in the regions of storm occurrence are comparable to the storm mechanisms that occur throughout the portions of the region where there is a paucity of large storm rainfall amounts. Further discussion of storm transposition is given in chapter 8.

2.3 Important Storms

From the list of major storms in table 2.1, a preliminary selection was made of the storms believed to be most important for the purpose of estimating PMP within the CD-103 region. The selection was based on the examination of DAD data and storm location, as well as from experience gained in previous studies. Forty-three storms were selected as important storms to consider when determining PMP over the CD-103 region. These storms are listed in table 2.2 and depth-area-duration data for most of the general storms in this list are given in Appendix B. The other storms were studied less intensively, primarily to define the regions of meteorological homogeneity. These storms are of lesser importance in determining the controlling level of PMP in the study region. The storm

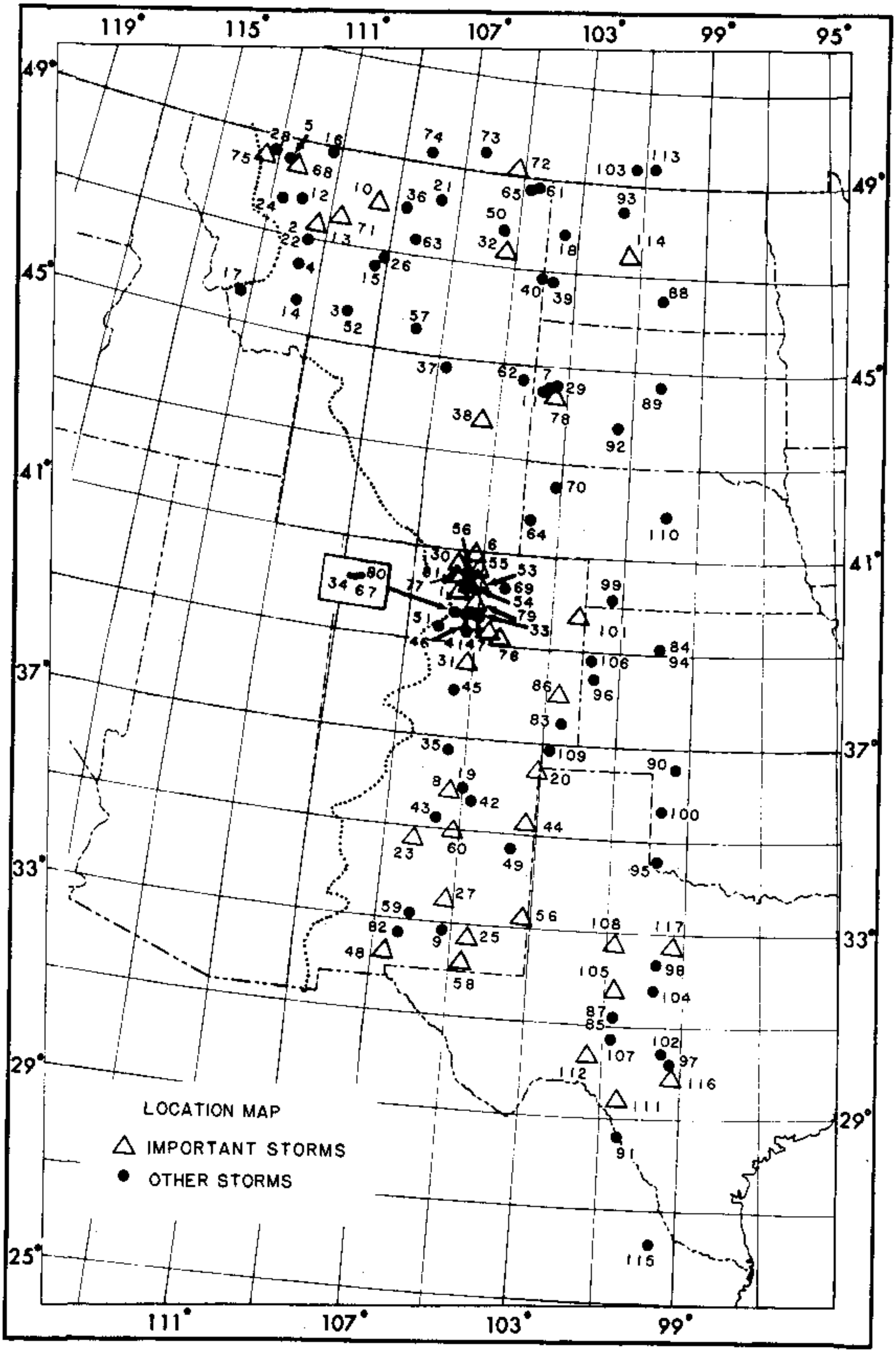


Figure 2.1.--Location of major storms that have occurred in and near the CD-103 region.

numbers used in table 2.2 are the same as those in table 2.1, and are therefore not sequential.

Table 2.2 provides the name of a city or town nearest the storm center, date of the storm, latitude and longitude, elevation, and 1,000-mi^2 24-hr and 10-mi^2 6-hr observed precipitation amounts. Precipitation values are given to provide some indication of the magnitude of the storm selected. For a few storms, no data are available for these specific area sizes and durations. Dashes are shown in the table for these storms. The elevations given in table 2.2 are not actual elevations at the location of the storm center, but are read from the barrier/effective elevation analysis (chapt. 3). When a barrier occurs upwind of the storm location, it is noted in table 2.2 by the letter "B" after the elevation.

2.4 Meteorological Analyses of Storms

The storms within this region can be grouped into two separate categories: (1) those associated with extratropical cyclones or extratropical convective activity and (2) those that are either the direct result of tropical cyclones or have as a primary moisture source the remnants of tropical cyclones that have crossed the Texas coast. In this section, the weather situation associated with some of the more important general storms will be discussed. The meteorological analyses of these and other major storms form the basis for the storm classification system described in section 2.5. The meteorological situations associated with local storms is discussed in Chapter 12.

2.4.1 Extratropical Storms

There are nine extratropical storms that are considered most important in the development of the PMP for the CD-103 region. The meteorological situation associated with each of these storms is discussed in this section.

2.4.1.1 Warrick, Montana - June 6-8, 1906 (10). During the period June 6-8, 1906, extensive rainfall occurred over most of Montana and western North Dakota, causing flooding with extensive damage to agricultural interests. At Warrick, MT (48° 04'N, 109° 39'W, elevation 4700), a total of 13.3 in. of rain was recorded during a 54-hr period beginning at 1:00 a.m. on June 6, and ending at 7:00 a.m. on June 8. On the morning of June 7, the heaviest rainfall occurred, 5.3 in. in a 6-hr period. Synoptic weather charts for 0600 MST (all times referred to in this report will be Mountain Standard Time) for the period June 4-8, 1906, are shown in figure 2.2. On the morning of June 4, a weak low pressure system was centered in western Canada, just north of Montana. A cold front extended southward through the United States toward the southern part of Nevada. As this Canadian low pressure system continued to move eastward, a weak Low formed on the Nevada-Utah border. This Low moved northeastward to east-central Montana. By the morning of June 6 it had split, and one Low was located over the Canada-Montana border at about 105°W, and a second Low was over the Wyoming-South Dakota border in the vicinity of Rapid City. A warm front extended almost due eastward from this second Low toward the Great Lakes. The cold front from that Low extended south and then southwestward through Nebraska, eastern Colorado, central New Mexico, into Arizona. General rains fell north of the warm front and extended westward from the Low well past the Continental Divide. Ahead of the cold front, southerly flow brought warm moist air from the Gulf of Mexico up through the Midwest and into the northern tier of states. This warm moist air

Table 2.2.--Storms important to determination of PMP for the CD-103 region

Storm Number	Name	Date	Lat. (°)	Lat. (')	Long. (°)	Long. (')	Elev.# (ft)	1000 mi² 24 hr	10 mi² 6 hr
1.	Ward District, CO	5/29-31/94	40	04	105	32	9600	4.6	1.7
6.	Boxelder, CO	5/1-3/04	40	59	105	11	7000	3.4	2.1
8.	Rociada, NM	9/26-30/04	35	52	105	20	7700	5.4	3.8
10.	Warrick, MT	6/6-8/06	48	04	109	39	4700	6.7	6.0
13.	Evans, MT	6/3-6/08	47	11	111	08	5000 B	5.3	1.9
86.	May Valley, CO	10/18-19/08	38	03	102	38	3800	5.9	4.2
20.	Clayton, NM	4/29-5/2/14	36	20	103	06	4800	7.9	5.3
23.	Tajique, NM	7/19-28/15	34	46	106	20	7500	4.1	4.6
25.	Lakewood, NM	8/7-8/16	32	38	104	21	3600	5.2	4.8
27.	Meek, NM	9/15-17/19	33	41	105	11	6700	5.0	3.8
30.	Fry's Rch., CO	4/14-16/21	40	43	105	43	8000	4.8	2.2
31.	Penrose, CO	6/2-6/21	38	27	105	04	5800	7.8	10.4
32.	Springbrook, MT	6/17-21/21	47	18	105	35	2900	11.3	10.5
35.	Virsylvia, NM (Cerro)	8/17/22	36	47	105	38	8800 B	-	-
38.	Savageton, WY	9/27-10/1/23	43	52	105	47	5100	6.6	6.0
44.	Porter, NM	10/9-12/30	35	12	103	17	4100	7.2	5.7
46.	Kassler, CO	9/9-11/33	39	30	105	06	5900	3.3	3.9
47.	Cherry Creek, CO	5/30-31/35	39	13	104	32	6900	7.2	20.6
101.	Hale, CO	5/30-31/35	39	36	102	08	4000	7.2	16.5
48.	Las Cruces, NM	8/29-30/35	32	19	106	47	4000 *	-	7.4
105.	Broome, TX	9/14-18/36	31	47	100	50	2400	13.8	16.0
53.	Loveland, CO	8/30-9/4/38	40	23	105	04	5000	3.1	6.4
55.	Masonville, CO	9/10/38	40	26	105	13	6000 *	-	-
108.	Snyder, TX	6/19-20/39	32	44	100	55	2400	-	18.8
56.	Prairieview, NM	5/20-25/41	33	07	103	12	4000	4.9	3.8
58.	McColleum Rch., NM	9/20-23/41	32	10	104	44	5800	6.3	10.1
60.	Rancho Grande, NM	8/29-9/1/42	34	56	105	06	5700	6.8	3.2
66.	Ft. Collins, CO	5/30/48	40	35	105	05	5000	-	7.8
67.	Golden, CO	6/7/48	39	44	105	14	6000 *	-	-
68.	Dupuyer, MT	6/16-17/48	48	12	112	30	4200	5.6	4.4
111.	Del Rio, TX	6/23-24/48	29	22	100	37	1100	17.9	13.2
71.	Belt, MT	6/1-4/53	47	25	110	50	4100	5.4	-
112.	Vic Pierce, TX	6/23-28/54	30	22	101	23	2200	18.4	16.0
72.	Buffalo Gap, Sask.	5/30/61	49	06	105	18	2900	-	-
75.	Gibson Dam, MT	6/6-8/64	48	32	113	33	7500 B	12.3	6.0

Table 2.2--Storms important to determination of PMP for the CD-103 region (continued)

Storm Number	Name	Date	Lat. (°)	Lat. (')	Long. (°)	Long. (')	Elev.# (ft)	1000 mi^2 24 hr	10 mi^2 6 hr
76.	Plum Creek, CO	6/13-20/65	39	05	104	20	6700	9.5	11.5
114.	Glen Ullin, ND	6/24/66	47	21	101	19	2000	-	11.1
77.	Big Elk Meadow, CO	5/4-8/69	40	16	105	25	8000	5.5	4.0
78.	Rapid City, SD	6/9/72	44	12	103	31	4800	-	-
79.	Broomfield, CO	5/5-6/73	39	55	105	06	5700	4.7	2.9
81.	Big Thompson, CO	7/31-8/1/76	40	25	105	26	8300 B	-	-
82.	White Sands, NM	8/19/78	32	47	106	11	4600 B	-	-
116.	Medina, TX	8/1-4/78	29	55	99	21	1800	15.0	17.0

\# Elevation is from smoothed barrier/effective elevation analysis. "B" indicates barrier elevation.

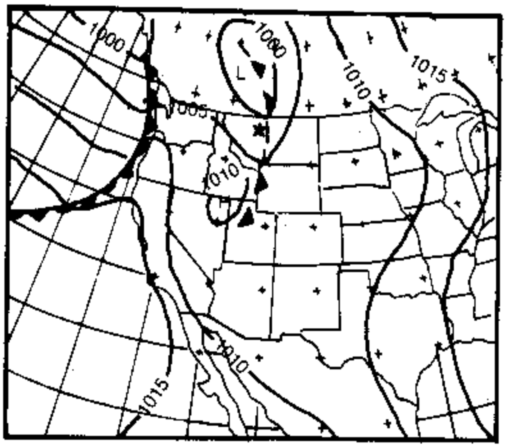
* Local storm elevation to nearest 100 ft.

was then pulled counterclockwise around the two low centers and westward into North Dakota and Montana. As the warm air moved northward, northwestward, and then westward around the Lows, it was forced over the cooler air mass already present in the region north of the low centers. This forced lifting of the warm moist air resulted in precipitation starting on June 6 in North Dakota and Montana.

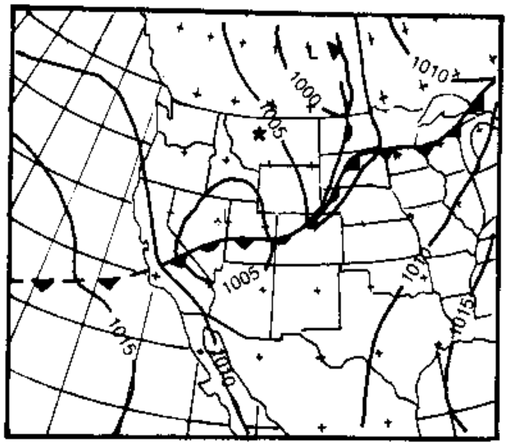
During the next 24 hr, the two low centers appeared to merge and deepen and the storm increased in intensity. The single low center remained almost stationary over western North Dakota, occluding as the cold front continued its eastward movement into Wisconsin, Illinois, and Missouri. The intensity of the Low caused high winds and strong convergence, as well as heavy precipitation over the region. During this time, winds at several locations in Montana and North Dakota exceeded 40 mph and rainfall at Warrick, MT reached its greatest intensity. Air flow was from the northeast to the northwest in the vicinity of the rainfall center during the time of maximum rain.

By the morning of June 8, the Low began to weaken and started drifting toward the northeast, which brought a dry northwesterly flow from Canada into Montana. The cold front continued its eastward movement, resulting in an occluded front that stretched into east central Canada. Showers occurred along this front. Rainfall in Montana generally ceased by late morning of the 8th.

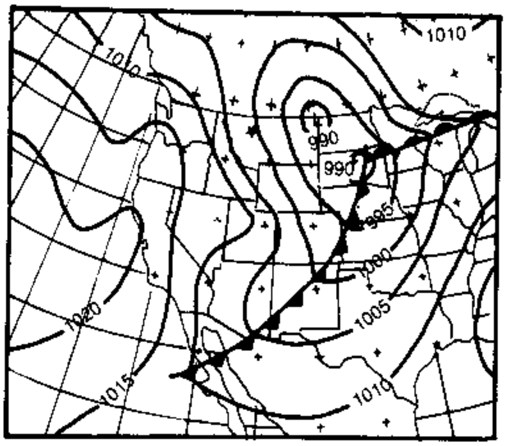
The isohyetal map for the storm is given in figure 2.3. This map shows that rain fell primarily in the plains areas of eastern and northern Montana. However, the maximum rainfall occurred at Warrick and fell around an isolated orographic feature, the Bear Paw Mountains. These mountains rise about 1,500 ft above the surrounding terrain. Although rainfall was significant (greater than 2 in.) throughout northeastern Montana, the rainfall at Warrick greatly exceeded other recorded amounts. This suggests that the Warrick center was a result of a local orographic influence upon thunderstorms embedded within the general-storm rainfall. This suggestion is reinforced by a rapid decrease in rainfall amounts



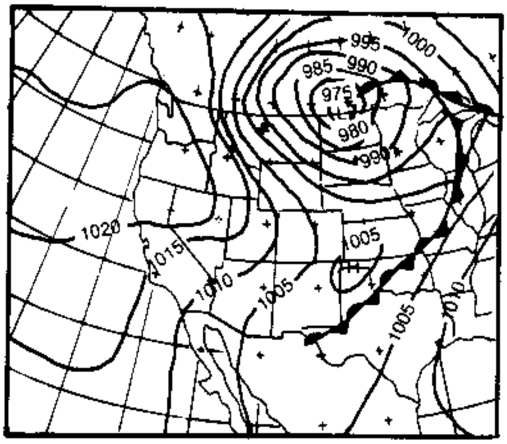
June 4 Surface 0600 MST



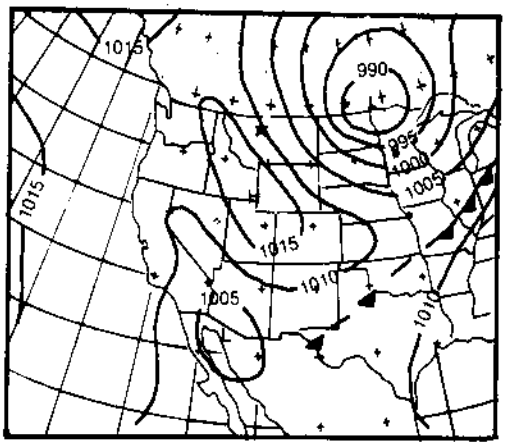
June 5 Surface 0600 MST



June 6 Surface 0600 MST



June 7 Surface 0600 MST



June 8 Surface 0600 MST

Figure 2.2. Synoptic surface weather maps for June 4-8, 1906 – the Warrick, MT storm (10).

Note: On this and subsequent figures showing weather patterns the location of the storm center is indicated by a star.

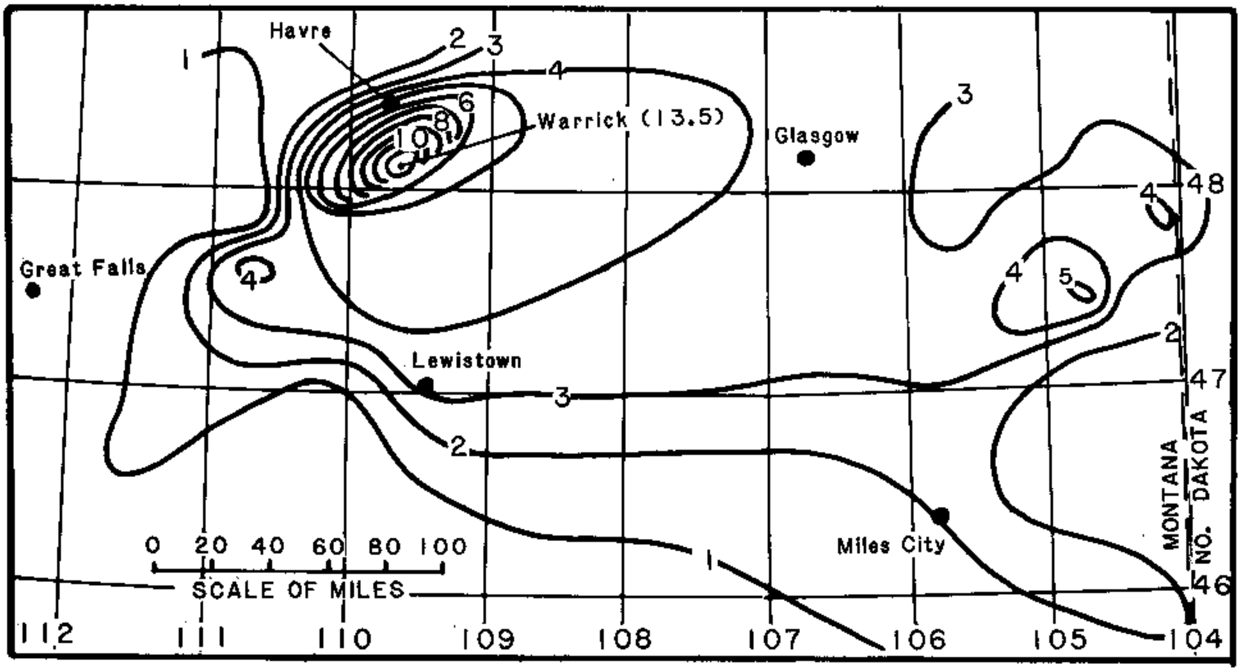
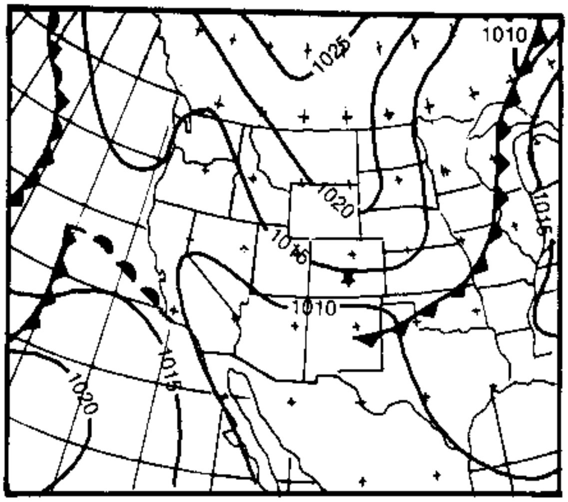


Figure 2.3.--Isohyetal map for the Warrick, MT storm (10) for period June 6-8, 1906.

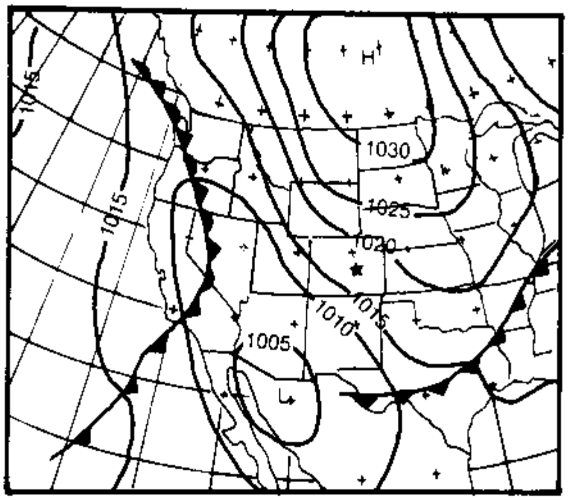
away from the Warrick center. With strong northerly winds, the rainfall center at Warrick was at least partially the result of spillover rainfall. The observed rainfall center was on the southward-facing slopes of the mountains. With northerly winds, the orographic influences in this storm could undoubtedly have produced greater rainfall amounts on the northward-facing slope, though the observation network in 1906 was too sparse to confirm this idea.

2.4.1.2 Penrose, Colorado - June 2-6, 1921 (31). The Penrose, CO storm was a very extensive storm occurring in parts of five states. Total duration of the storm was 114 hr taking into consideration rainfall which occurred over an area of approximately 140,000 mi^2. It did not rain over the entire area concurrently; rather, there were several rainfall centers located within the five state area. The Penrose center, which was the largest, recorded 12 in. in an 18-hr period beginning about 6:00 p.m. June 3 and ending around noon of June 4.

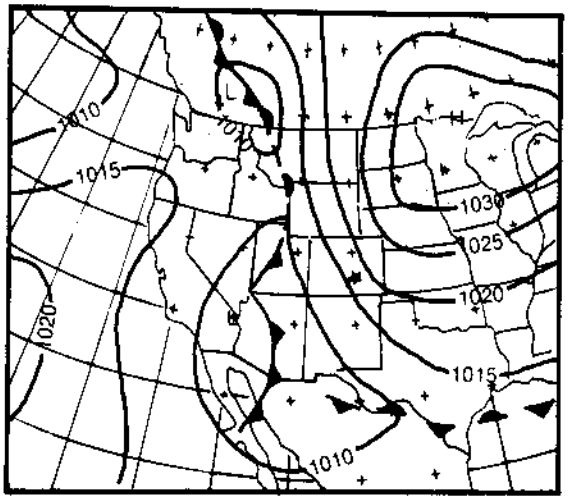
On June 3, a cold front progressed slowly southeastward across the western United States (fig. 2.4). Meanwhile, a large high pressure area moved generally southward to a position in the vicinity of the Great Lakes. On the morning of June 4, this zone of high pressure became elongated along an east-west axis and dominated the weather and flow pattern from the Great Lakes southward to the Gulf of Mexico. This east-west elongation of the High produced an easterly flow over most of the southern and midwestern United States. At the western edge of the Great Plains, the airflow turned and became southwesterly. This flow brought the moist warm air from the southern United States northwestward. The terrain caused this moist air to be lifted, at first gradually over the higher terrain of western Texas and Oklahoma and then abruptly, by the first upslopes of the Rocky Mountains. It was this moist unstable air that produced the Penrose rainfall center on the evening of June 3 and the morning of June 4.



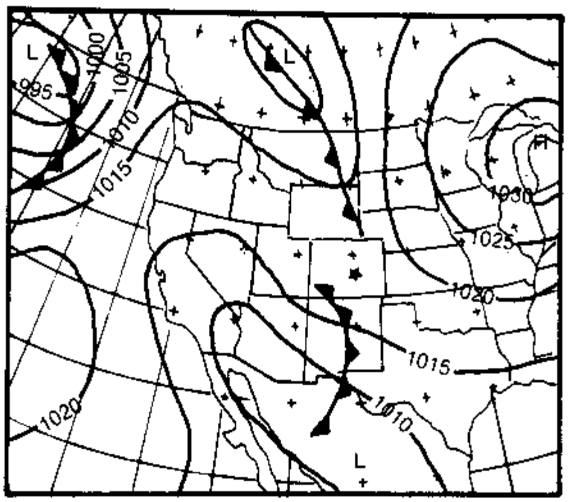
June 2 Surface 0600 MST



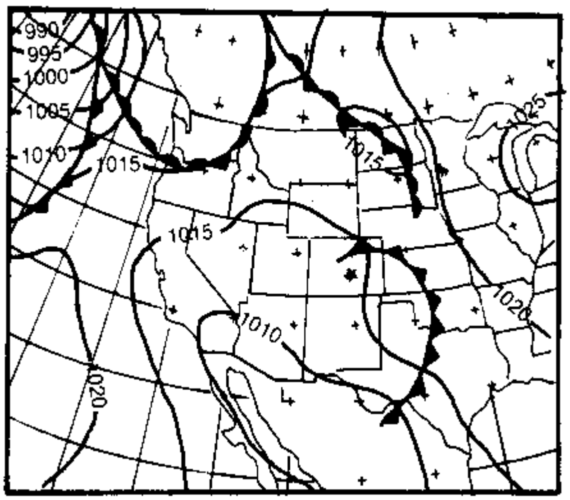
June 3 Surface 0600 MST



June 4 Surface 0600 MST



June 5 Surface 0600 MST



June 6 Surface 0600 MST

Figure 2.4.--Synoptic surface weather maps for June 2-6, 1921 - the Penrose, CO storm (31).

By the morning of the 5th, the high pressure center from the Great Lakes had begun to drift eastward. This resulted in reduced flow into the Penrose storm. The easterly component of the flow over the western part of the Great Plains weakened, and a more southerly component began to dominate. This reduced the lifting effect of the first upslopes of the Rockies; however, the moisture inflow was still sufficient to produce scattered rains in Colorado, New Mexico, Texas, and Oklahoma. The heaviest rains were occurring farther south in New Mexico and Texas, and were associated with a cold front that was moving into the region on the 5th and 6th. These rainfalls were not nearly as intense as those that had occurred in Colorado on the evening of the 3rd and the morning of the 4th. The High, which had been centered near the Great Lakes, continued to drift farther to the east, resulting in diminished strength of the moist airflow from the Gulf of Mexico northward. As the cold front moved through New Mexico, Texas, and Oklahoma, it pushed out the final remnants of the moist easterly flow.

The isohyetal pattern (fig. 2.5) shows rainfall centers in four states that exceeded 6 in. The centers are located at Penrose, CO (12 in.); Hope, NM (6.4 in.); Shattuck, OK (7.3 in.); and Plainview, TX (6.3 in.). A fifth center of 5.9 in. was located at Cimmaron, KS. Mass curves of rainfall for representative stations in the centers at Penrose, Hope, and Shattuck (fig. 2.5) indicate the differing natures of the precipitation in the different centers. The rainfall at the Penrose center, and other large amounts in Colorado, generally occurred over a relatively short duration (less than or equal to 24 hr). At Hope, Shattuck, and Plainview (mass curve not shown), the precipitation occurred over a longer time period, generally in excess of 48 hr. At Penrose, 87 percent of the total storm rainfall occurred in the maximum 6-hr period, while at other locations in Colorado with large precipitation amounts, the greatest 6-hr amount accounted for 60 to 85 percent of the total storm amount. The average of the greatest 6-hr amounts for Colorado stations was approximately 78 percent of the total storm rainfall. By contrast, in the other three centers of the storm, the ratios of the greatest 6-hr amounts to the total storm precipitation amounts are significantly less, being 29 percent at the Plainview, TX center, 31 percent at Hope, NM, and 47 percent at Shattuck, OK. Other reports of heavy rainfall outside of Colorado show 6-hr to total storm ratios ranging from approximately 20 to 74 percent. An average of these ratios outside of Colorado was approximately 46 percent.

2.4.1.3 Springbrook, Montana - June 17-21, 1921 (32). This was a large area extratropical cyclone that occurred over eastern Montana and western North Dakota. The primary rainfall center occurred at Springbrook, MT where 15.1 in. of precipitation fell in approximately 100 hr. Over 85 percent of the total storm rainfall fell in a period of about 18 hr. The precipitation centers in North Dakota were considerably smaller; 5.3 in. at Powers Lake, ND and 4.9 in. at Beach, ND.

At 0600 on June 17, a slow-moving cold front extended from eastern Montana southwestward through Arizona (fig. 2.6). Warm moist air from the Gulf of Mexico was being pumped northward by a high pressure system centered over Mississippi. A wave, which was forming on the front, was positioned in northeastern Arizona. The wave moved quickly northeastward along the front, and, by 0600 June 18, was situated in southeastern Wyoming with a warm front extending eastward along the South Dakota-Nebraska border. The moist unstable air from the Gulf of Mexico was lifted over the warm front and deflected around the Low in Wyoming. Convective activity was occurring in the vicinity of both the warm and cold fronts.

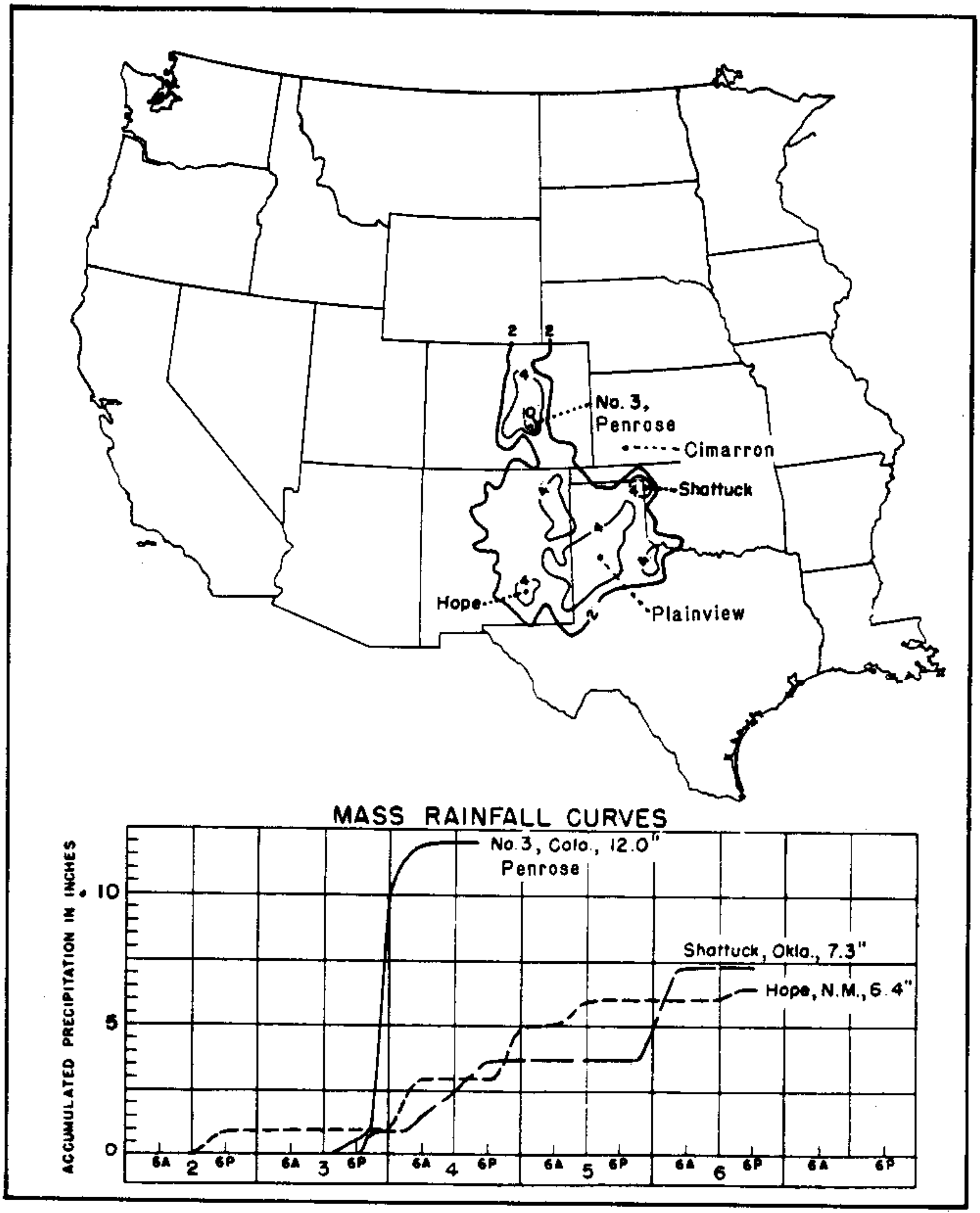


Figure 2.5.--Isohyetal map and selected mass rainfall curves for June 2-6, 1921 - the Penrose, CO storm (31).

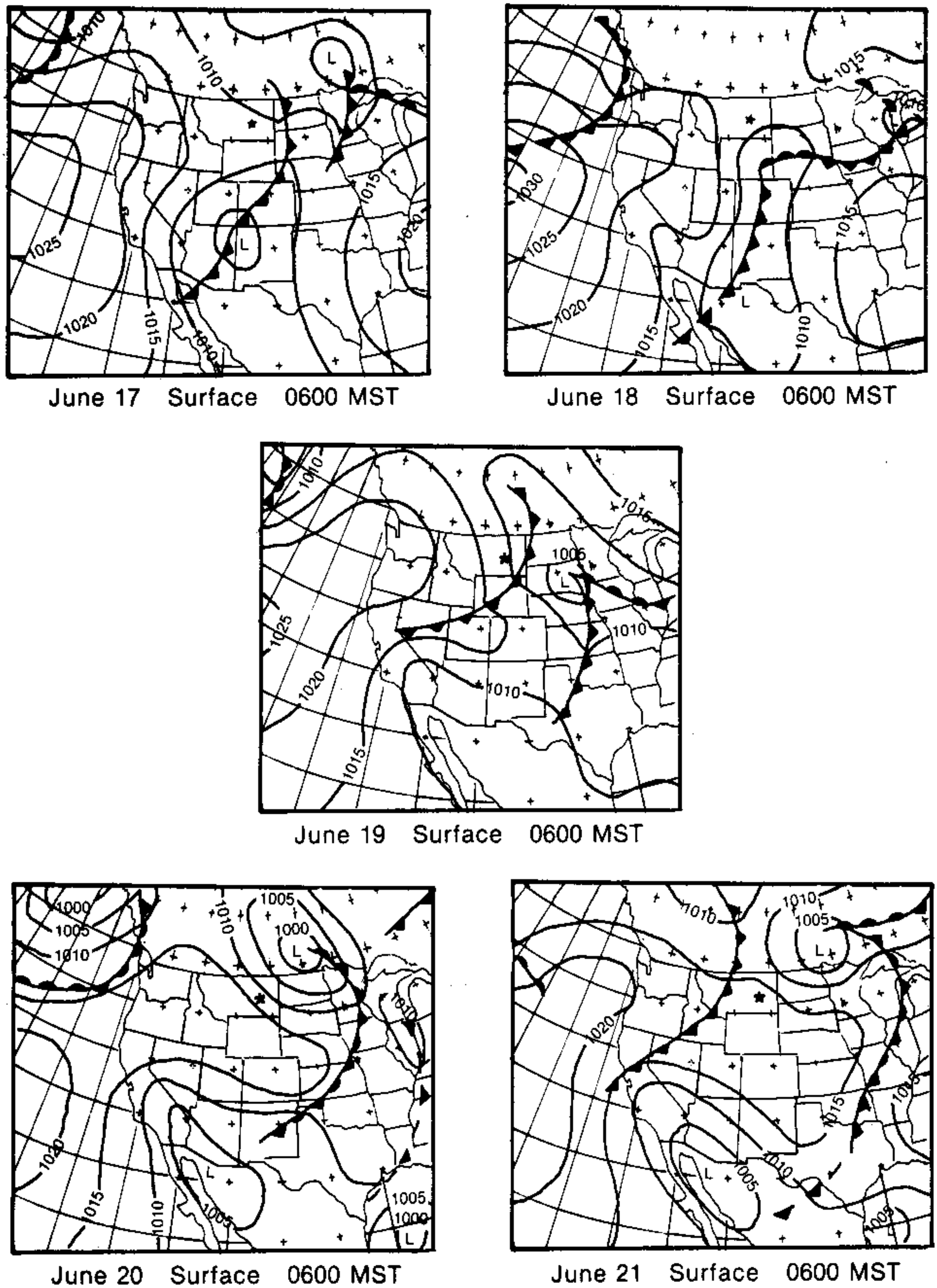


Figure 2.6.--Synoptic surface weather maps for June 17-21, 1921 - the Springbrook, MT storm (32).

By the morning of June 19, the Low (fig. 2.6) had occluded and was centered in western South Dakota with a trough of low pressure extending northwestward over southeastern Montana. The moist tropical air continued to flow cyclonically around the occluded system. Meanwhile, another rapidly moving cold front from the Pacific Ocean, associated with a Low moving from the Pacific Ocean across northern Canada, crossed into Montana and provided additional lifting of the warm moist air. Upon reaching the trough in southeastern Montana, this system regenerated and a new Low developed. The older Low moved southeastward and dissipated as the new Low deepened and traveled northeastward. By the evening of June 19, it was centered over northwestern North Dakota. The sharp cyclonic lifting and turning of the tropical air around the Low caused intense heavy rainfall over northeastern Montana during the afternoon and night of June 19. On June 20 and 21, the new Low gradually moved eastward along the United States-Canada border. As the system moved out of the region, drier air replaced it and the rainfall ended except for scattered convective showers.

The circular shape of the isohyets drawn around the maximum rainfall center (fig. 2.7) is probably a reflection of the sparsity of measurements. The maximum value of 15.1 in. at Springbrook, MT is 2.5 times greater than the next largest recorded value of 5.9 in., which occurred over 40 mi away. If a greater number of measurements had been made in this region, the structure of the isohyetal pattern probably would have been more complicated. It is also possible that a larger rainfall center would have been discovered. The 2-in. isohyet (fig. 2.7) encompasses a large area including parts of Wyoming, Montana, North Dakota, and Canada. The storm amounts are those measured for a 108-hr period, although the majority of the rain fell during roughly 15 hr in two bursts, one during midday of the 18th, and the second during midday of the 19th through the early morning of the 20th.

2.4.1.4 Savageton, Wyoming - September 27-October 1, 1923 (38). A significant feature of the Savageton, WY storm was the cyclonic circulation of the low pressure system which produced widespread convergence. Another important factor was the strong flow of warm moist air northward from the Gulf of Mexico into the region of heavy precipitation. The heaviest precipitation occurred at Savageton, WY in the northeastern portion of the state. The maximum precipitation for this 108-hr storm period was 17.1 in.

On the morning of September 25, the low pressure system which would affect the Savageton, WY area was positioned just off the northern California coast. An accompanying front extended eastward from the Low across California and Nevada through Utah, and northeastward to join another Low in North Dakota. A High was centered over Lake Ontario and was pumping warm moist air northward from the Gulf of Mexico through Texas and as far north as Minnesota. A stationary front oriented south to north from western Texas to North Dakota marked the western border of the humid air mass at the surface.

The Low over the Pacific moved inland to northern Utah by 0600 September 26. The accompanying warm front stretched eastward to Nebraska and into Canada. The High strengthened while moving eastward and maintained the steady flow of warm moist air from the Gulf of Mexico. Meanwhile, the stationary front was dissipating so the warm moist air was able to penetrate further to the north and west. By the morning of September 27, the Low had traveled to southeastern Colorado (fig. 2.8) and the warm front associated with the Low extended eastward through northern Missouri. The cold front associated with the Low extended southward

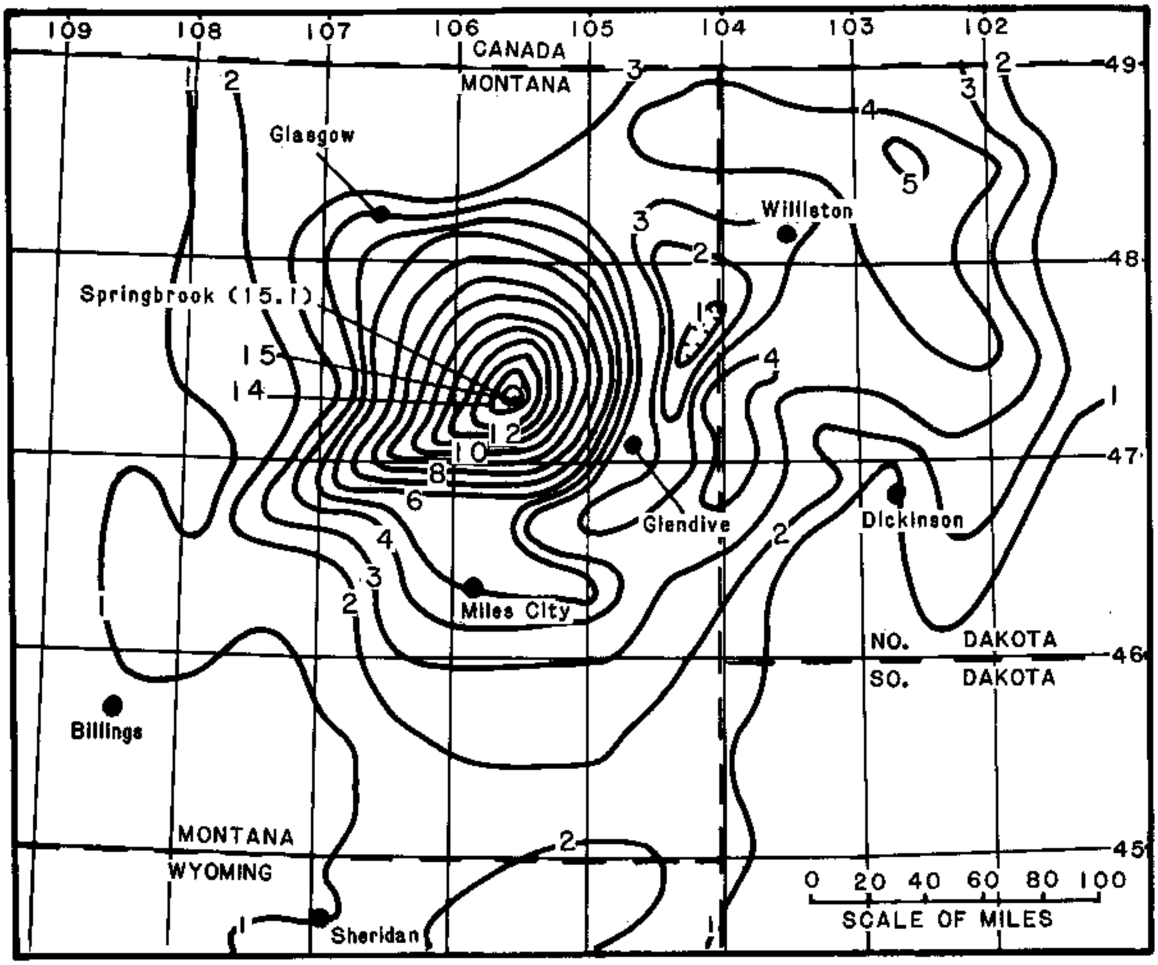


Figure 2.7.—Isohyetal map for June 17-21, 1921 - the Springbrook, MT storm (32).

through New Mexico, Texas, and into Mexico near El Paso. The High continued to strengthen as it drifted southeastward into the Atlantic Ocean. Circulation around the High persisted over the west central Plains and continued to move the warm moist Gulf of Mexico air northward to the vicinity of the Low and fronts. In the northern Rocky Mountains, a mass of cold air was moving from north to south immediately to the rear of the Low. Although some precipitation associated with this low pressure system occurred as the storm crossed California, the heavy rains east of the Continental Divide began on the 27th as warm moist air from the Gulf was lifted over the cold air, while the pronounced cyclonic circulation produced a strong level of convergence.

The Low moved very little in the 24 hr from the morning of the 27th through the morning of the 28th and, at 0600 on the 28th, was centered in northwestern Kansas. The accompanying warm front from the Low had moved slightly northward to the Iowa-Missouri border, while the cold front still trailed southward through Oklahoma, the Texas Panhandle, and through the Big Bend country of Texas. The high pressure system started to weaken as it drifted further southeastward; however, the flow from the Gulf of Mexico northward remained strong. The heavy rains in Wyoming continued as circulation around the Low stayed intense.

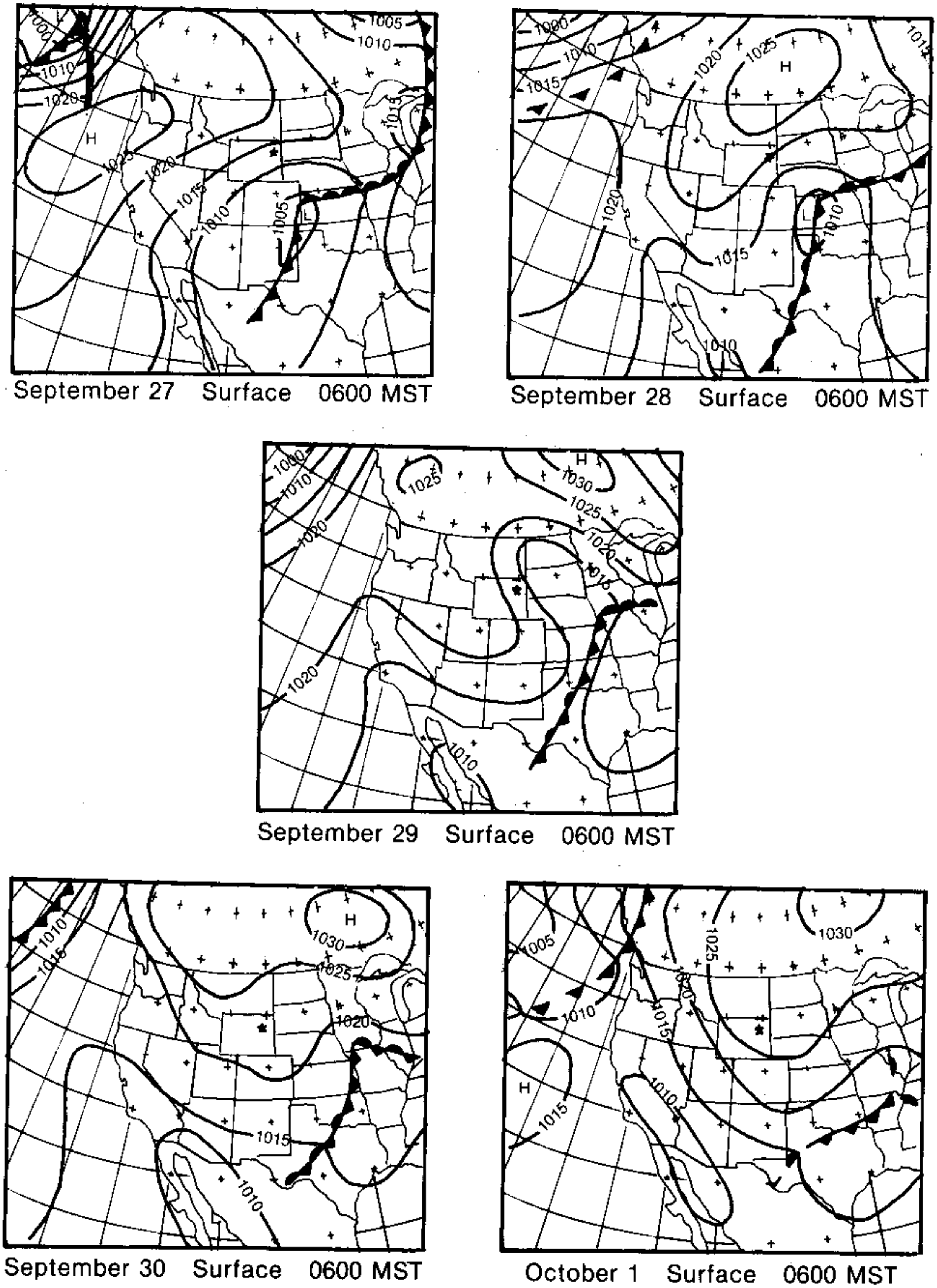


Figure 2.8.--Synoptic surface weather maps for September 27-October 1, 1923 - the Savageton, WY storm (38).

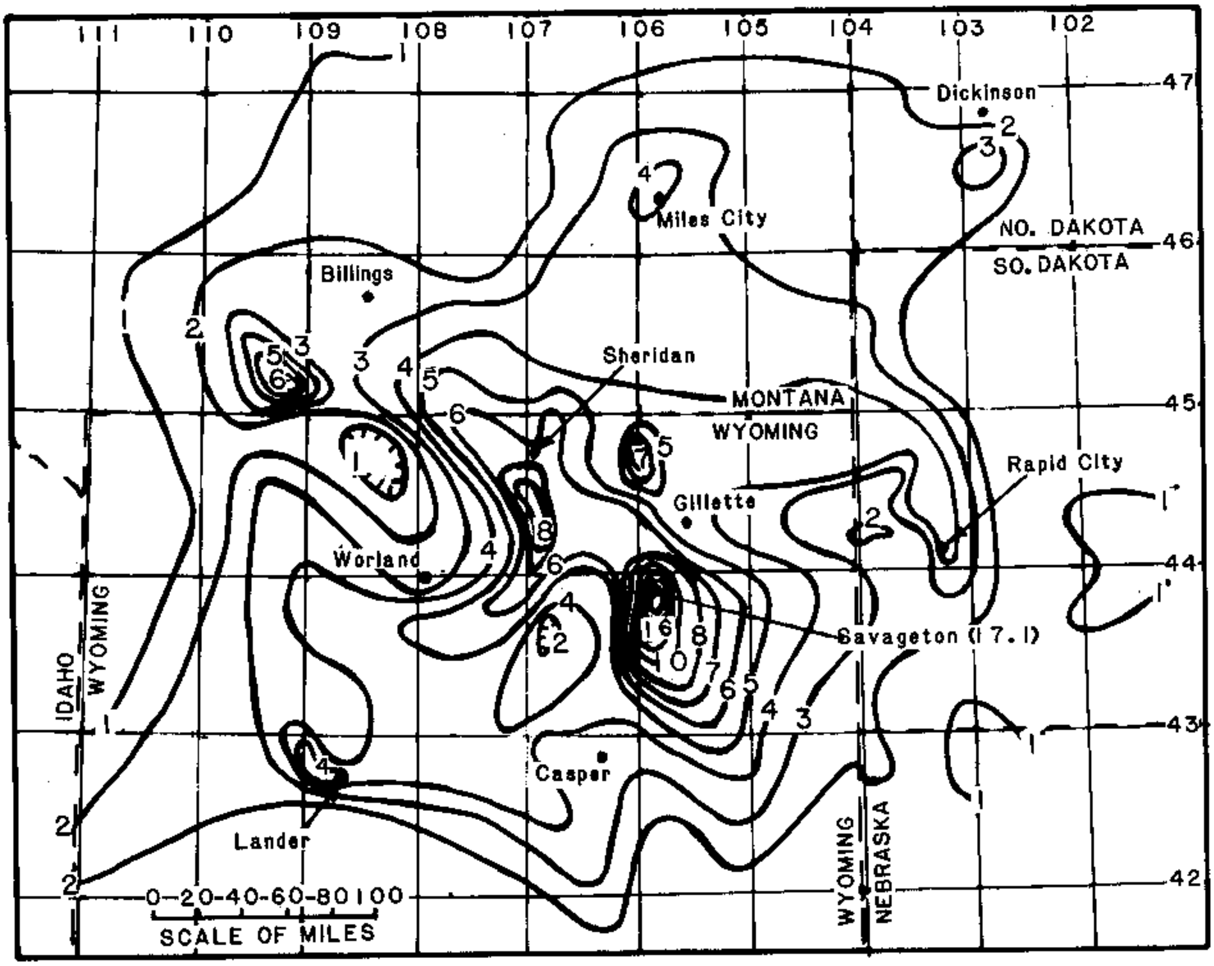


Figure 2.9.--Isohyetal map for September 27-October 1, 1923 - the Savageton, WY storm (38).

The storm began to decrease during the 28th, and by the morning of the 29th a distinct closed circulation pattern was no longer evident. The rainfall began to diminish significantly in Wyoming. What remained of the system was a rather diffuse region of low pressure that extended from eastern Nebraska northwestward into west central South Dakota. The eastward movement of this region of low pressure was blocked by a ridge of high pressure which had built southeastward from Manitoba into Ohio. A tropical storm off the coast of South Carolina had caused the eastern High to weaken and move eastward into the Atlantic. This resulted in disruption of the southerly flow across the Gulf States and limited the flow of air northward from the Gulf of Mexico.

On September 30 and October 1, the precipitation which occurred was in the form of isolated rain and snow showers. The remnants of the low pressure system moved into southeastern Nebraska. Warm moist airflow from the Gulf of Mexico had been completely shut off.

The maximum precipitation for the 108-hr storm period was 17.1 in. at Savageton, WY. Another large amount in Wyoming was 8.3 in. at Hunters Station, while 8.0 in. fell at Arvada, CO. The area receiving at least 2 in. of precipitation was equivalent in size to the entire state of Wyoming (fig. 2.9).

The maximum average depth of rainfall was 6.6 in. for 24 hr. over 1,000 mi^2. Since the storm was primarily the result of convergence from the low pressure system, the total isohyetal pattern was basically oriented from southwest to northeast, roughly paralleling the track of the storm. Along the mountain ranges maxima tended to be influenced by the mountain slopes and were located on the eastern slopes.

2.4.1.5 Cherry Creek (47) - Hale (101), Colorado - May 30-31, 1935. During a 24-hr period beginning at 6:00 a.m. on May 30 and ending at 6:00 a.m. on May 31, heavy convective rainfall broke out at several locations along a line from the foothills of the Rocky Mountains of eastern Colorado east-northeastward to the Kansas border. These storms were small in areal extent, but of extreme intensity, with point rainfall amounts as high as 24 in. in a 6-hr period. The rains caused much flash flooding in the Cherry, Kiowa and Bijou Creek basins just east of the foothills of the Rocky Mountains in Colorado, and on other small basins to the east near Hale, CO.

The surface weather map (fig. 2.10) for the morning of May 30 shows the presence of a weak low pressure center with associated cold and warm fronts. The Low was centered over northern Utah with a warm front extending eastward south of the area of heavy precipitation. Warm moist air flowed into the region from the Gulf of Mexico. As the morning wore on, the warm front drifted northward to a position almost directly over the Cherry Creek-Hale, CO area. The Low drifted southeastward, and the center was located in northern New Mexico. The intersection of the cold and warm fronts was just west and south of the precipitation center. North of the warm front a strong High was centered over the Canada-United States border. The presence of these dissimilar air masses caused the outbreak of the extreme convective activity along the warm front in the late morning. The storm then moved east northeastward along the warm front, feeding on the low level moist air that was moving northward from the Gulf of Mexico and on instability released as warm air moved up over the cold air associated with the high pressure system. This continued until the early morning hours of the 31st when the storm dissipated.

The many reports of hail are witness to the intensity of these storms. Some reports indicated hail as large as baseballs. It is also likely that low level winds near the storm and along the warm front were very strong. The report of a heavy dust storm near the Colorado-Kansas border during the storm period supports this conclusion.

There were several rainfall centers in the storm as shown on the isohyetal map (fig. 2.11). The two largest centers with greatest rainfall depths are the Kiowa center and the Hale center, both reaching 24 in. Because flooding on Cherry Creek was more critical to Denver, the storm is generally referred to as the Cherry Creek storm in the literature, whereas the largest rain amounts actually fell on the Kiowa and Bijou Creek basins. The Kiowa center (39°13'N 104°32'W), at an elevation of 6,900 ft, occurred in an orographic region known as the Palmer Ridge, while the Hale center (39°36'N 102°08'W) occurred at an elevation of 4,000 ft in essentially flat nonorographic terrain. This suggests that, although the Kiowa center may have been initiated and enhanced by orography, this storm as a whole was not dependent on strong orographic lifting.

Timing of the rainfall determined by mass curve analysis (not shown) shows that the heavy rain began in the Kiowa, Bijou, and Cherry Creek areas about midmorning

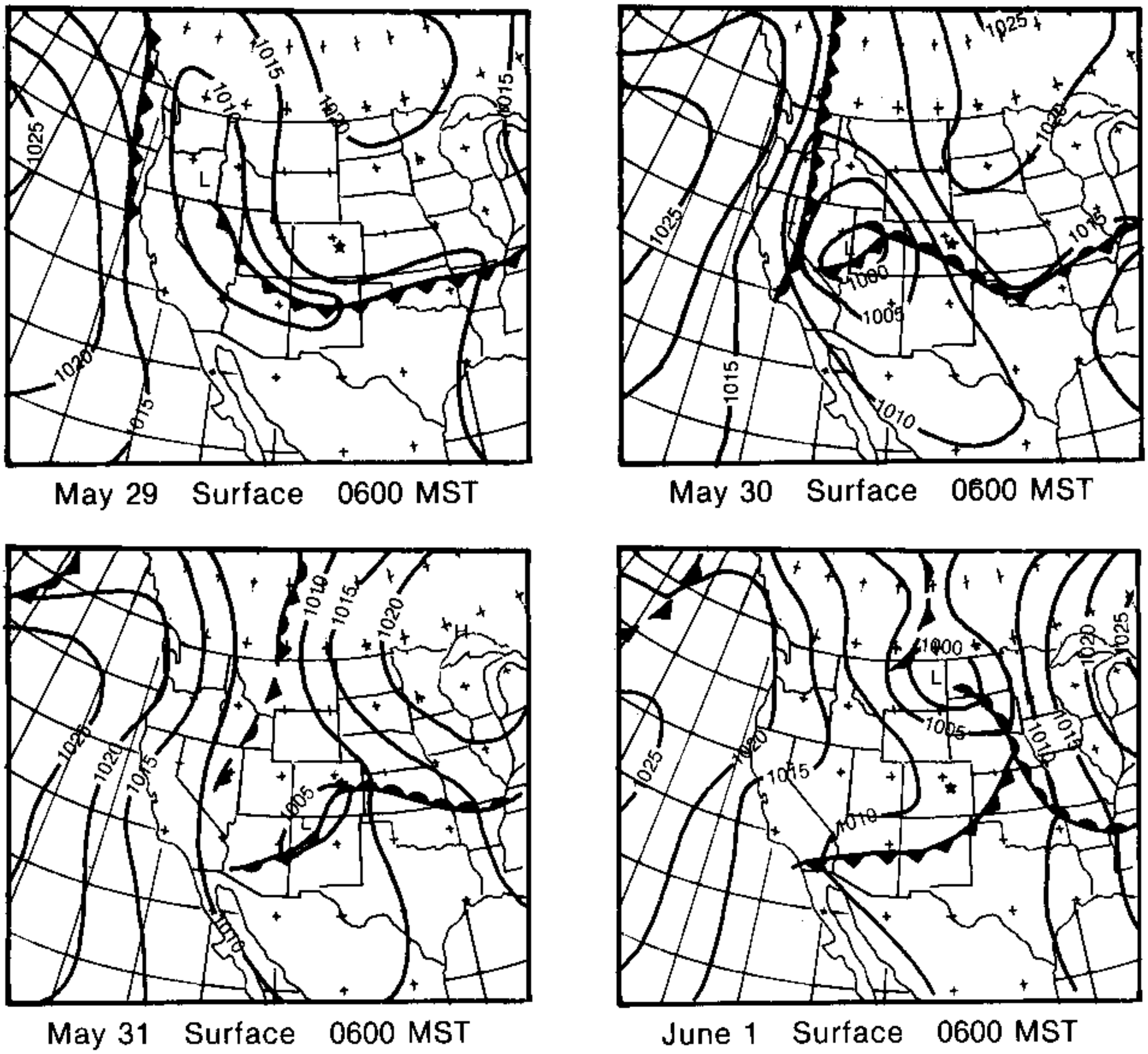


Figure 2.10.--Synoptic surface weather maps for May 29-June 1, 1935 - the Cherry Creek (47) - Hale (101), CO storm.

of May 30. The time of beginning of rainfall became later and later on the 30th in an eastward progression from the Kiowa Creek area. At the Hale center rainfall began about 6:00 p.m. on the 30th. Rainfall had effectively stopped over the Kiowa center by that time. This timing factor suggests that there was an east-northeastward propagation of the severe instability and of the primary tongue of moisture that caused the heavy storms that had developed late in the morning of the 30th over Kiowa.

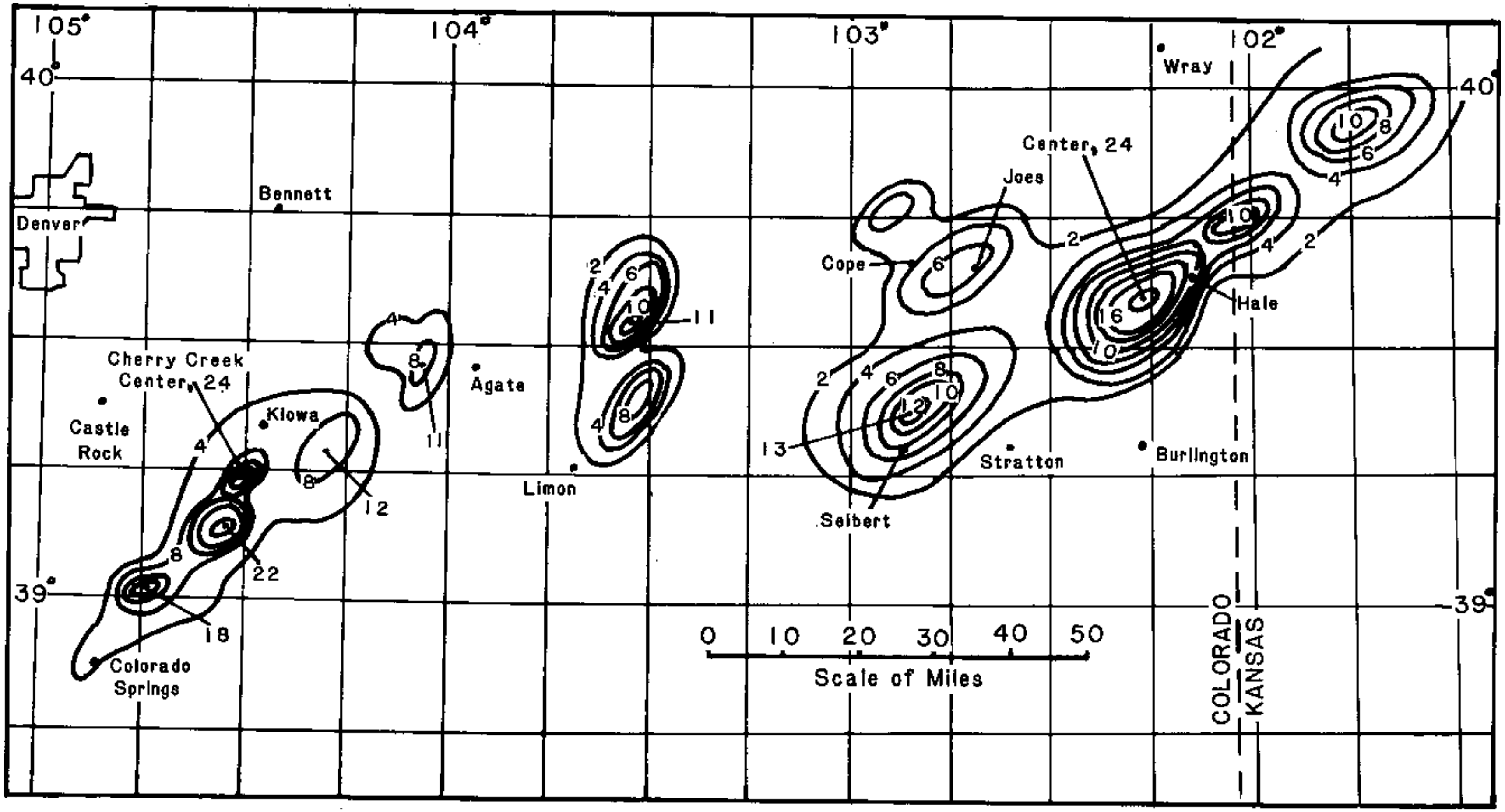
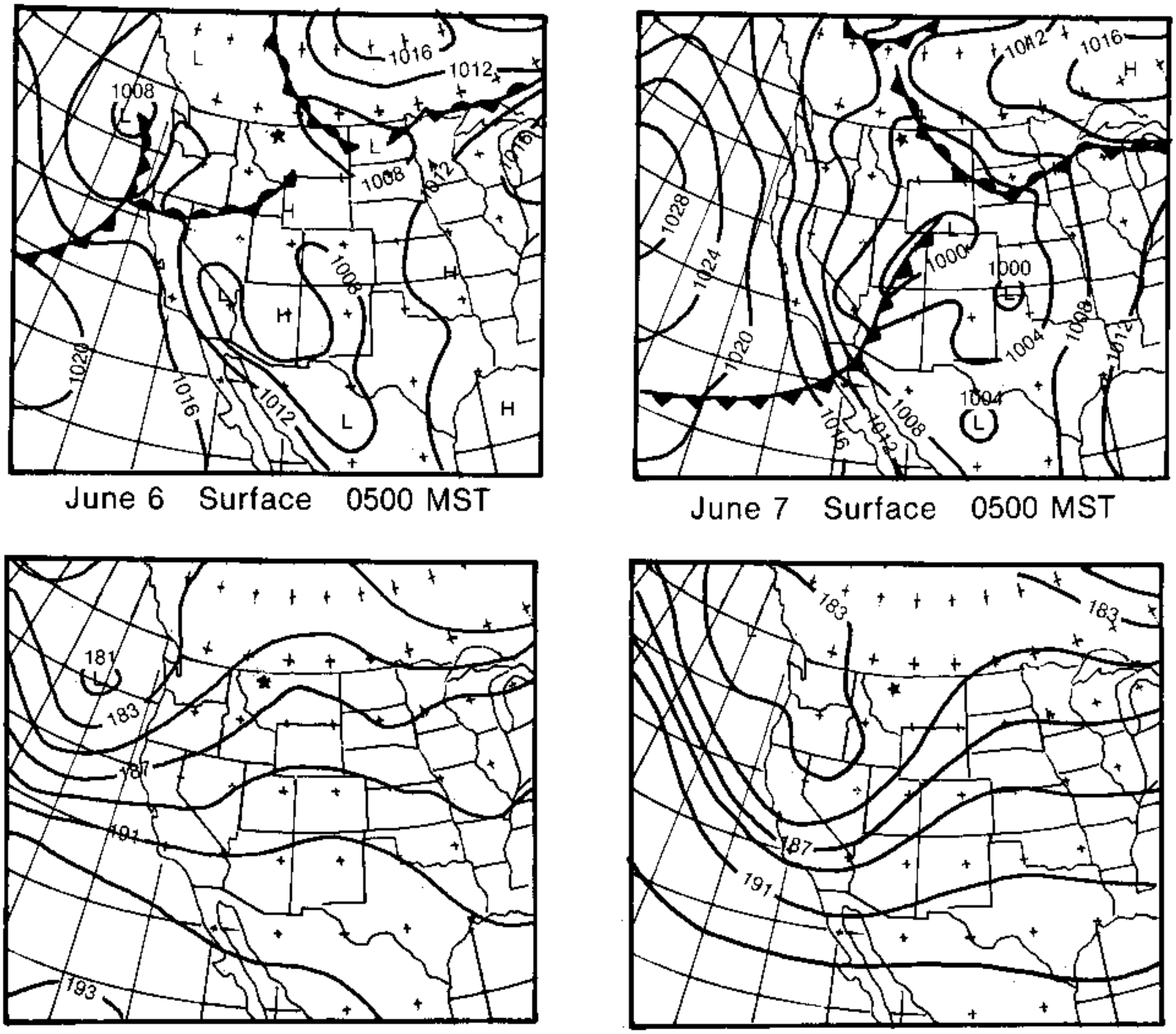


Figure 2.11.—Isohyetal map for the Cherry Creek (47) - Hale (101), CO storm for period May 30-31, 1935.


June 6 Surface 0500 MST

June 7 Surface 0500 MST

June 6 500 MB 0500 MST

June 7 500 MB 0500 MST

Figure 2.12.--Synoptic surface weather maps and 500-mb charts for June 6-7, 1964 - the Gibson Dam, MT storm (75).

2.4.1.6 Gibson Dam, Montana - June 6-8, 1964 (75). Beginning in the early morning hours on June 7, 1964, rainfall occurred over the mountainous region of western Montana* causing severe flooding over a large portion of the Missouri river basin of west-central Montana. The storm continued until the late evening of June 8, with a total storm duration of about 36 hr. A maximum storm amount of 16.2 in. has been determined from an isohyetal analysis.

The storm is discussed at length in U.S. Geological Survey Water Supply Paper 1840-B (Boner and Stermitz 1967); therefore, only a brief discussion is included here. The surface and 500-mb weather patterns are shown in figures 2.12 and

*Note: The maximum analyzed rainfall in this storm occurred at 48°32'N 113°33'W or about 16 mi northwest of East Glacier Park, MT, rather than near Gibson Dam. However, this storm has continued to be referred to as the Gibson Dam storm because of a preliminary analysis.

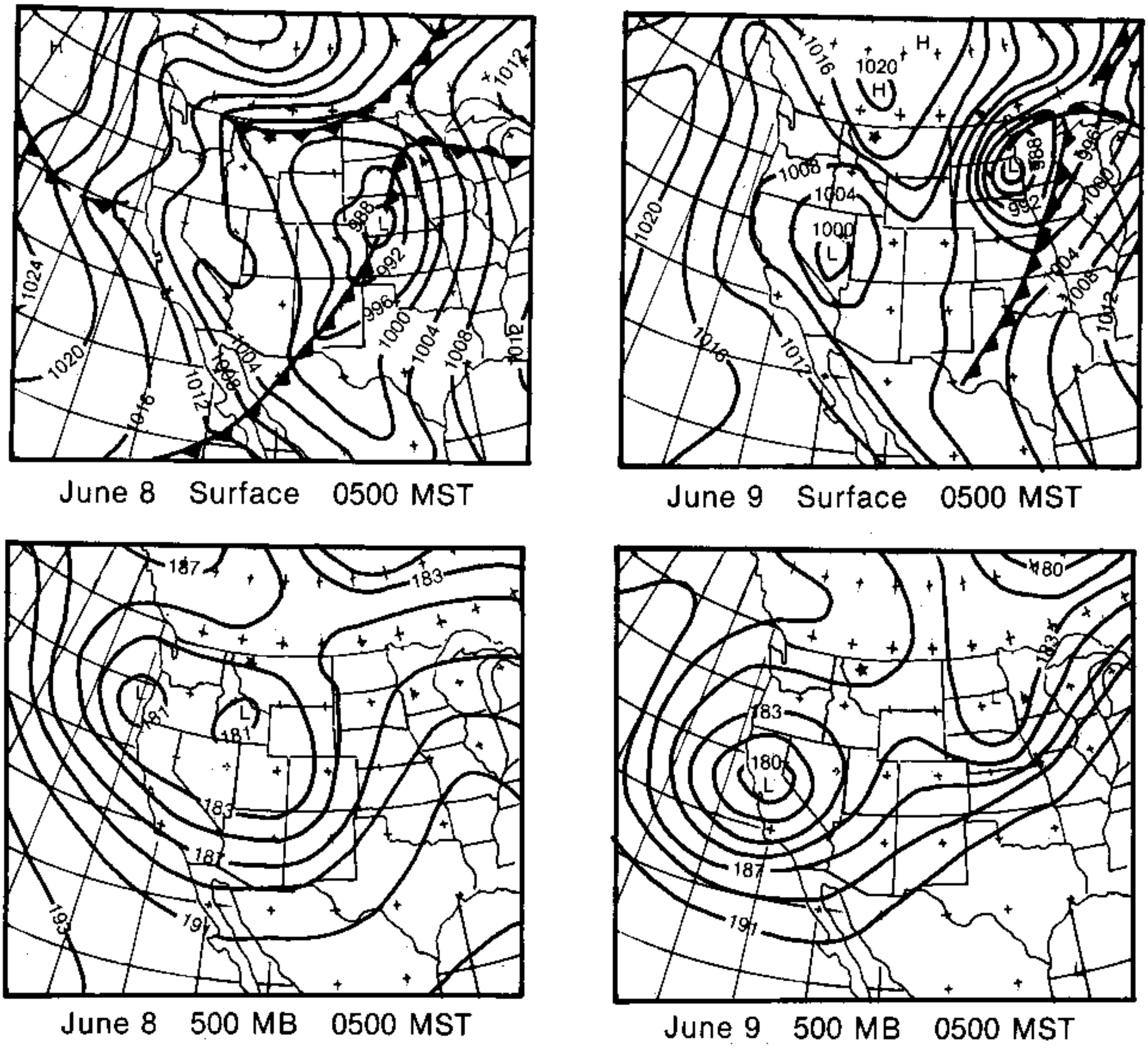


Figure 2.13.--Synoptic surface weather maps and 500-mb charts for June 8-9, 1964 - the Gibson Dam, MT storm (75).

2.13. It is evident from an examination of the surface weather charts that the main feature of this storm was a strong low pressure center, which passed to the south and southeast of the storm location. The circulation around the Low brought moist air from the Gulf of Mexico northward across the Great Plains and then westward over Montana into the storm region. As the moist air turned westward around the north side of the Low, it was carried up and over the mountains of western Montana. The rainfall was the result of both the convergence around the Low and lifting by the mountain slopes.

The isohyetal pattern in figure 2.14 was analyzed considering, in a general sense, the orographic lifting of the storm. The location of the major rainfall centers, however, was dictated by rainfall observations and streamflow records. All of the major centers are located in the mountains of western Montana. This shows the significance of the topography in the rainfall process for this storm. The amounts decreased to the east as the orographic influence became less and less. The heaviest rainfall during the Gibson Dam storm (75) occurred on the morning of the 8th, during the time of a strongest easterly flow.

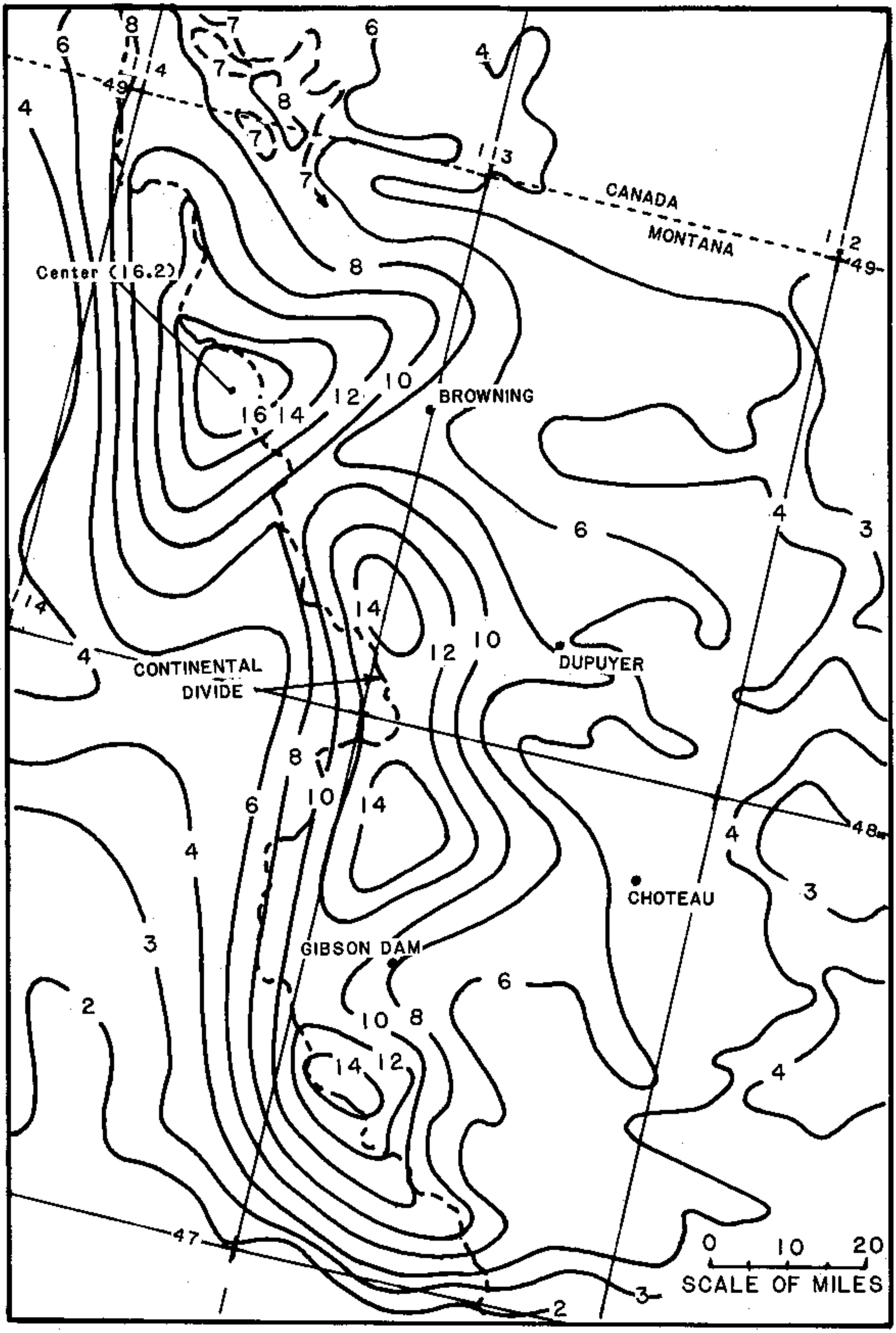


Figure 2.14.--Isohyetal map for June 7-8, 1964 - the Gibson Dam, MT storm (75).